**The Thesis Committee for Michael Gerald Kurker**
**Certifies that this is the approved version of the following thesis:**

# Evaluation of Freeway Work Zone Merge Concepts

**APPROVED BY**
**SUPERVISING COMMITTEE:**

**Supervisor:** ______________________________
Randy Machemehl

______________________________
Zhanmin Zhang

# Evaluation of Freeway Work Zone Merge Concepts

by

**Michael Gerald Kurker, B.S.C.E**

**Thesis**

Presented to the Faculty of the Graduate School of
The University of Texas at Austin
in Partial Fulfillment
of the Requirements
for the Degree of

**Master of Science in Engineering**

**The University of Texas at Austin**
**December 2013**

## Acknowledgements

The following thesis could not have been completed without the dedication and assistance of several people. First, I would like to thank my advisor, Dr. Randy Machemehl, for his endless support, encouragement, and willingness to always discuss any questions or issues that I encountered throughout my time at the University of Texas at Austin. Next, I would like to thank Dr. Zhanmin Zhang, the second reader of this thesis. In addition to support from the two readers of this thesis, I would like to thank my TxDOT Project # 0-6704: Reduction of Motorists' Delay and Crash Potential Upstream of Highway Work Zones team for their support in collaboration throughout my research. Lastly, I would like to thank my family and friends, especially those in Connecticut, for their endless support, love, and encouragement to achieve the goals that I set both in Austin and throughout my life. Without them, I would not have achieved many of the successes so far in my life.

# Abstract

## Evaluation of Freeway Work Zone Merge Concepts

Michael Gerald Kurker, M.S.E
The University of Texas at Austin, 2013

Supervisor: Randy Machemehl

Using microsimulation software, with a focus on VISSIM, the analysis of different applications of merge concepts through delay and safety is presented in this thesis. In order to appropriately draw conclusions and usage trends of different merge concepts from the microsimulation software, early merge, late merge, and signal merge were first explored in a thorough literature review. While focusing primarily on delay, queues, and safety, this thesis essentially provides an introduction to determining the ideal merge concept on freeway work zones for varying roadway configurations, roadway conditions, and user demands, among other factors. In addition to delay and queuing analysis completed using VISSIM, the Federal Highway Administration's Surrogate Safety Assessment Model (SSAM) was used to address the effects of implementing signal merge on rear-end and lane-change conflicts. Compiling the VISSIM microsimulation outputs and SSAM signal merge safety outputs, general conclusions and decisions were provided. While this thesis provides determinations of ideal merge concepts for a variety of cases, it is important for the next researcher to assess some of the assumptions that were made, to ensure that they would not significantly affect the results and analysis.

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# Chapter 1. Introduction

Work zone lane closures on freeways yield difficulty in providing efficient traffic operations and safe conditions for drivers and workers. Lane closures due to freeway work zones reduce available capacity, which increases congestion and poses several issues in maintaining unobstructed traffic operations. Merging at these closures increases weaving, may cause queue jumping, and presents the risk of rear-end collisions. Drivers subjected to these merging conditions at freeway work zones may exhibit unsafe behavior that stems from “road rage.” According to a Dallas study by the Texas A&M Transportation Institute (TTI), around half of drivers surveyed view merging as the most stressful situation facing drivers. This stress is primarily due to drivers using the closed lane to pass the slower moving traffic in the open lane, in an effort to force their way in downstream, which is otherwise known as queue jumping (Walters et al., 2000). In an effort to both improve efficiency and safety through freeway work zones, while minimizing user stress, different applications of merge concepts were used. Depending on demand conditions, roadway configuration, and specific driver behaviors that need to be minimized, early merge, late merge, and signal merge control can improve freeway work zone efficiency.

# Chapter 2. Literature Review

## 2.1 Introduction to Lane Control

Lane control techniques facilitate the merging process to reduce freeway user stress levels. By guiding the driver at or to a specific point, instances of queue jumping and weaving are lessened, which can increase capacity. These processes are implemented through variations of either early merge, late merge, or signal merge control strategies. Both forms of control can be implemented as either static or dynamic. Static utilizes signs that display a single message at all times and in the same location regardless of traffic conditions. Dynamic takes into account real-time control measures to decide whether or not to activate additional signage upstream to further inform approaching drivers.

### 2.1.1 Early Merge Control

Early merge is a strategy that warns drivers in advance of a work zone of an upcoming lane closure. This allows time for the user to find a gap and complete the merging process ahead of the closure. This technique is found effective if traffic demand is low compared to capacity. The system breaks down with high demand and fewer gaps (Yang et al., 2009).

As an application of early merge, a study by Tarko and Venugopal for the Indiana Department of Transportation (INDOT) looked at using variable messaging signs to warn drivers to merge ahead of the queue, as shown in Figure 2.1 (Tarko et al., 2001). These signs were triggered to flash the message “No Passing When Flashing,” using sensors that activated the next sign upstream of a forming queue. This created a “no passing zone” with enough room for local police to enforce the signage. By merging sooner, aggressive maneuvers were minimized throughout the merge process. This strategy was found useful with low to moderate traffic demands.

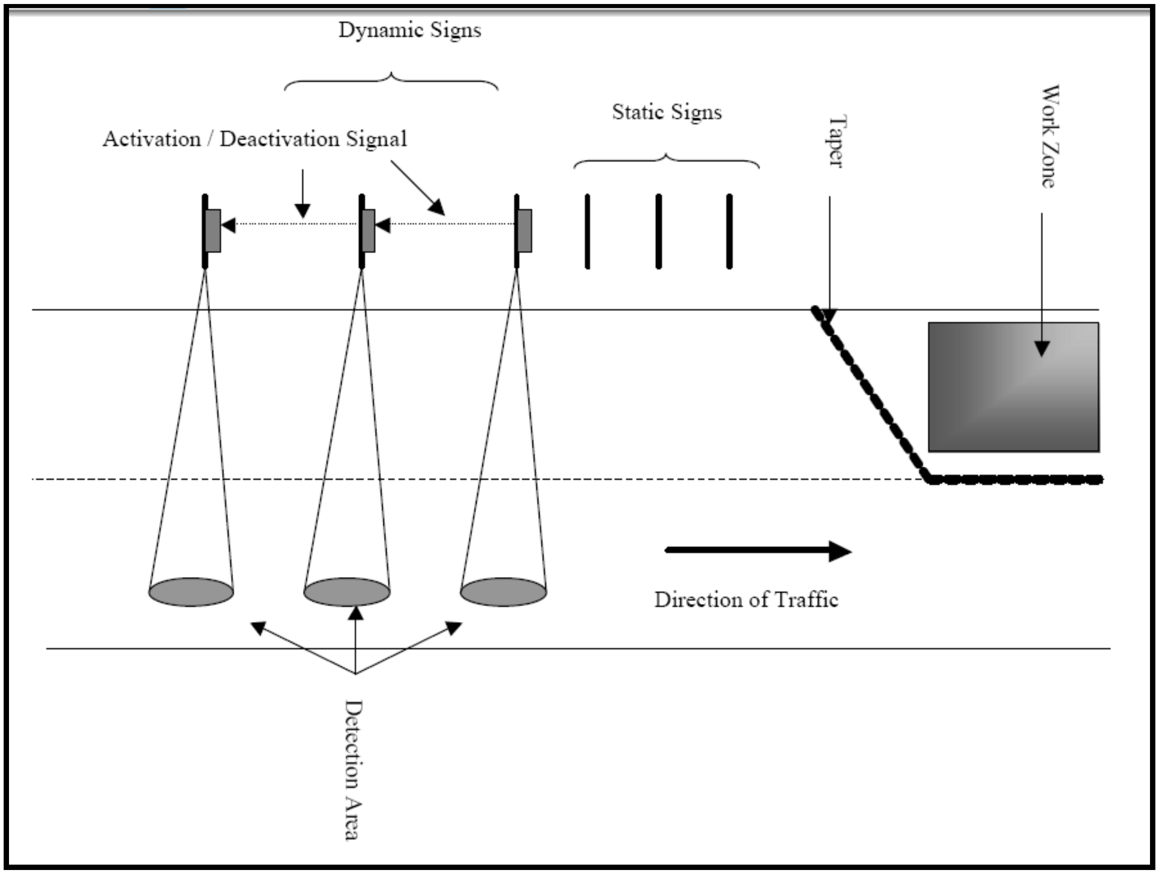



**Figure 2.1 Indiana Lane Merge System (Tarko et al., 2001).**

INDOT tested this system on 2-to-1 lane work zones, while the Michigan Department of Transportation (MDOT) experimented on 3-to-2 lane configurations with approximately the same setup and results (Datta et al., 2004). MDOT first tried this technique in 2000 at five locations along the freeway system. To help ensure compliance, these locations were enforced by officers and violators risked a $200 fine (Walters et al).

### 2.1.2 Late Merge Control

Late merge is a technique that tries to take advantage of the full capacity of the freeway approaching a work zone to minimize the length of queue formation in conditions where demand approaches capacity. This is accomplished by advising drivers to use all available lanes followed by a "take turns" method once users arrive at the merge point.

Delft University in the Netherlands explained this as the “Zipper” method, meaning that drivers do not change lanes until a fixed distance from the lane drop, closer to the lane closure than early merge. Proper usage of the late merge system can improve throughput significantly while reducing queue length of up to 50 percent (Walters et al., 2000).

In a comparative study by McCoy and Pesti (2001), early merge was noted as being efficient only in low to moderate traffic demands. Once the system approaches capacity, significant queues would develop and would increase the risk of high speed drivers encountering stopped queues. Their proposed solution was a dynamic late merge setup, where sensors would switch the system from early merge at low volumes to late merge at high volumes. This could be accomplished by real time sensors that would activate variable message signs (VMSs) to inform drivers whether or not to maintain lane choices. One innovative concept was the use of construction placement of sensors in construction barrels or Smart Drums, to monitor traffic as shown in Figure 2.2. They noted that signs would have to be placed well before the anticipated queue to avoid the aforementioned collision risk. However, anticipating an appropriate queue length is not always an easy task; the Maryland Highway Administration had to move signs prior to the Smart Drums three times due to underestimating queue lengths. They went on to recommend that warning signs be placed on both sides of the freeway to avoid blockage by heavy vehicles and that speed reduction as vehicles approached the merge point, increased throughput (Kang et al., 2006).

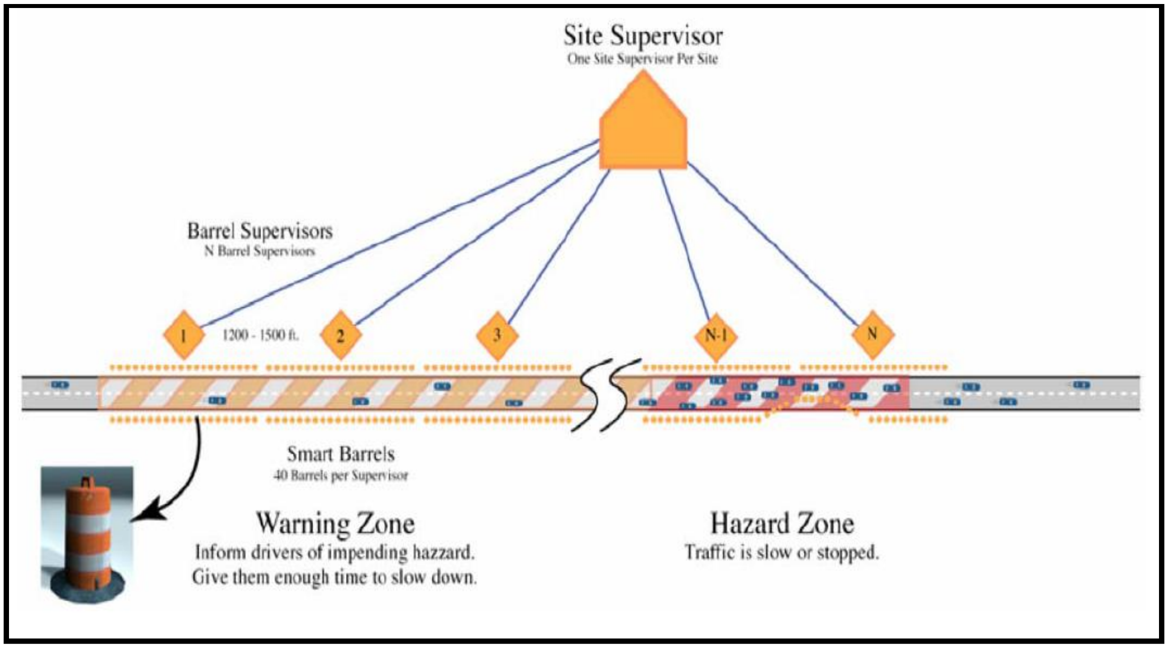



**Figure 2.2 Application of Smart Drum (Kang et al., 2006).**

Several studies by Departments of Transportation found that the measures of effectiveness comparing the Smart Drum method for late merge and uncontrolled merge were not significantly different. It is difficult to assess the effectiveness of a late merge method on a general basis though, because characteristics are different at each site, including driver behavior, geometry, and percentage of trucks, among others. Eric Meyer from the University of Kansas, in conjunction with the Kansas Department of Transportation, ran into a similar challenge when researching work zone behavior for Kansas City. He noticed that drivers would move into the left closed lane even when instructed to remain in the right lane. The site was near an entrance ramp, which caused drivers to react to outside sources other than sign postings. Meyer also documented that drivers went through a “training” period to get acquainted with the control method before any significant effects (improvements) from the Smart Drum technology could be observed, compared to an uncontrolled merge. The percentage of drivers following the Smart Drum late merge control doubled from the first week to the second (Meyer, 2004).

### 2.1.3 Signalized Merge Control

Signalized guidance is a relatively new concept where traffic signals that are usually located at intersections, are placed at work zones to facilitate the movement of traffic. Signalized control was created to manage merging where sites are heavily congested and thus, where demand exceeds capacity. The conventional merge scenarios such as early merge and late merge are beneficial as long as traffic demands remain less than the work zone capacity. A study conducted in 2009 suggests that early and late merge control methods peak in efficiency between 700 and 800 passenger cars per hour per lane (pcphpl), where the experimental procedure of lane-based signal merge (LBSM) could handle well above that limit and were efficient with high percentages of heavy vehicles (Yang et al., 2009).

A study led by Heng Wei at the University of Cincinnati combined signal control with dynamic late merge. In this study, real time sensors were used to detect traffic demand. Once the system noted certain control measure limits, a central unit activated upstream signs to warn drivers to maintain their lane position. Once at the merge point, a traffic signal would alternate lanes allowing users to enter the work zone one lane at a time. The system was named the Dynamic Merge Metering Traffic Control System (DMM-Tracs) and was noted to work well with cycle lengths of either 60 or 120 seconds, while the optimal lengths were between 60 and 120 seconds. Antonis Lentzakis at the Technical University of Crete in Greece also studied metering effects with signals, but used local metering algorithms (ALINEA) to optimize signal timing (Lentzakis et al., 2008).

All signalized studies rely heavily on simulation software for testing. There were no studies found that showed actual field testing of signalized merge control, though each study was promising under heavily congested traffic conditions. Regardless of the roadway demand and lane control measures used, a percentage of roadway users will choose a different path because of the presence of a work zone.

# Chapter 3. Microsimulation

This section focuses on the microsimulation modeling efforts to evaluate innovative control measures, including early merge, late merge, and signal merge or Fixed-Cycle Signal Merge Control (FCSMC), which has been shown to be more effective for congested corridors. The FCSMC is based on the late merge strategy and was simulated for a work zone using VISSIM and CORSIM software, under a variety of traffic demands. VISSIM is a microscopic, time-step, and behavior-based simulation model that can analyze traffic and transit operations under various constraints, including lane configuration, traffic signalization, and user demand. (Bloomberg and Dale, 2000).

Similar to the capabilities of VISSIM, CORSIM is a microscopic simulation model designed for analysis of freeways, urban streets, corridors, and networks (Bloomberg and Dale, 2000). In order to quantify work zone traffic operations, both VISSIM and CORSIM can address individual corridors, as well as network issues. Although both VISSIM and CORSIM were used to gain an initial understanding of work zone traffic operations, VISSIM was used as a primary decision-making tool for the determination of ideal merge concepts. The primary data collection via simulation used VISSIM because of its ability to provide 3-dimensional graphics and animations. While this capability was not necessary, it provided an opportunity to minimize the learning curve for unfamiliar simulation software. These graphics or visualizations made it easier to locate queue development, significant conflicts, and sources of delay on the freeway. Although CORSIM has been applied in the United States for much longer than VISSIM, VISSIM provides similar output criteria after calibration and validation. The base case in VISSIM was calibrated based on demand, configuration, and other variables to provide a reliable simulation method with 3-dimensional animation. Regardless of the simulation software used, measures of effectiveness like delay, queue lengths, speed, and travel time are deemed appropriate for the purpose of comparison across scenarios. Since signal merge is a relatively new application, CORSIM was exclusively used to verify trends found in VISSIM.

### 3.1 Description of Network Configuration

Traditional MUTCD traffic control includes advance warning signs that guide drivers to merge into open lanes when suitable. Signs are placed on both sides of the roadway 1.5 miles ahead of the merge taper to inform travelers of the lane closure(s). Approximately 1,500 feet in advance of the taper, lane reduction signs are placed on both sides of the roadway. A flashing arrow panel is usually placed at the beginning of the taper to instruct drivers in the closed lane to merge into the open lane. This traffic control concept works adequately for undersaturated conditions. However, in congested conditions when long queues extend beyond warning signs, aggressive driving maneuvers in closed lanes attempting to merge into the open lanes may result and consequently, cause a further reduction in capacity.

The Fixed-Cycle Signal Merge Concept is imbedded in the late merge traffic control. In the late merge concept, travelers are encouraged to use all lanes up to the merge point at the lane closure taper, instead of merging as soon as possible, which is encouraged by traditional early merge controls. A late merge configuration was developed by the Pennsylvania Department of Transportation (PennDOT). In this traffic control strategy, approximately 1.5 miles in advance of the lane closure, "USE BOTH LANES TO MERGE POINT" signs are placed on both sides of the roadway. These signs are followed by conventional "ROAD WORK AHEAD" and advance lane closed signs. Finally, "MERGE HERE TAKE YOUR TURN" signs are placed on both sides of the roadway near the beginning of the taper. The primary intent of the late merge configuration developed by PennDOT is to reduce road rage between early and late mergers by informing drivers that it is permissible for traffic to travel in both lanes to the merge point. The merge concept configuration used in this analysis is similar to that of

PennDOT and is shown in Figure 3.1 (Beacher et al., n.d.). In this research however, the roadway section prior to the work zone was extended to accommodate potential long queues that could form under high traffic demands.

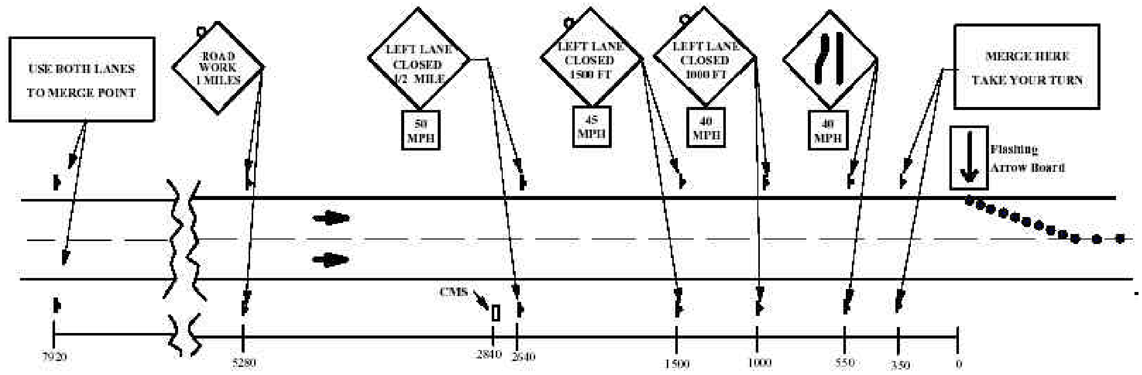



**Figure 3.1 Late Merge Traffic Control Plan from Pennsylvania Department of Transportation (Beacher et al., n.d.).**

The fixed cycle signal merge metering strategy testing consisted of several fixed cycle lengths, including 30, 60, 90, and 120 seconds; in addition to these cycle lengths, 150 and 180 seconds were tested using CORSIM. These signal displays consisted of green, amber, and red intervals, just like a signal at any intersection. For evaluation purposes in this study, the green interval is equally divided among lanes as the traffic volumes were coded as equal among lanes. However, in actual conditions the traffic volume distribution is not always equal on all lanes. Therefore, the green interval duration could possibly be divided in the same ratio as the traffic volume distribution by lane. The travel speed was assumed 55 mph throughout the work zone study corridor.

### 3.2 Modeling Procedure

Microsimulation analysis was conducted using both CORSIM and VISSIM software. Even though these analyses are not based on an actual site, by adjusting some driving behavior parameters, the models were enhanced to ensure the simulators mimic realistic driver behaviors observed, as a result of early merge, late merge, and signal merge implementation. A brief discussion of modeling efforts is presented below.

### 3.2.1 CORSIM

To model signal merge in CORSIM, input flows of 1800, 2000, 2200, and 2400 pcphpl, or vehicles per hour per “open” lane (vphpl), were used. These parameters were inputted for various lane configurations, including 2-to-1, 3-to-1 and 3-to-2 lane merge configurations. In each scenario the left lane(s) were dropped leaving the right most lanes accessible to travel through the work zone. A “base case” simulation was first simulated using late merge control concepts without signalized operations. Lanes were then separated with one signal placed in each lane to control merging. The signals provided a green indication to one lane at a time for the 2-to-1 and 3-to-1 configurations in 30, 60, 90, 120, 150, and 180 second cycle lengths, with available green times divided evenly among the lanes with four second ambers. For the 3-to-2 configuration, signalization was maintained with 2 lanes operating at a time staggered from each other, with equal distribution of green times followed by four second ambers. An example of the 3-to-2 signal times is illustrated in Figure 3.2 with a 30 second cycle length. As previously discussed, cycle lengths for the 3-to-2 configuration and all other configurations vary from 30 to 180 second cycle lengths in 30 second increments.  Desired speeds of 65 mph were maintained for all segments except the work zone segment which was reduced to 55 mph. Results are the averages of three simulation runs.

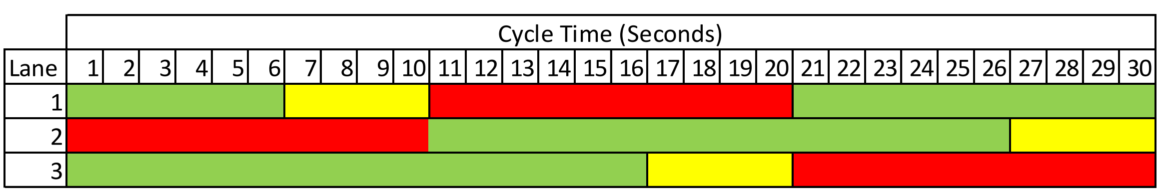



**Figure 3.2  Signal Time Allocation for 3-to-2 Lane Configuration with 30 Second Cycle.**

### 3.2.2 VISSIM

VISSIM simulation efforts were focused on 2-to-1, 3-to-1, and 3-to-2 lane configurations for all merge concepts, with fixed cycle lengths of 30, 60, 90, and 120 seconds for signal merge. Three replicate simulations runs were performed for each combination of lane configuration and user demand; thus, 45 total runs were completed for early merge, late merge, and signal merge combined.

## 3.3 Results from CORSIM and VISSIM

Results of these analyses for CORSIM and VISSIM simulations are presented below.

### 3.3.1 CORSIM

Several measures of effectiveness were monitored for signal merge during trial runs including total travel time, total delay, ratio of input to output flow, and driver behavior. The results gathered for the 3-to-1 lane configuration are shown below in Figures 3.3, 3.4, and 3.5.

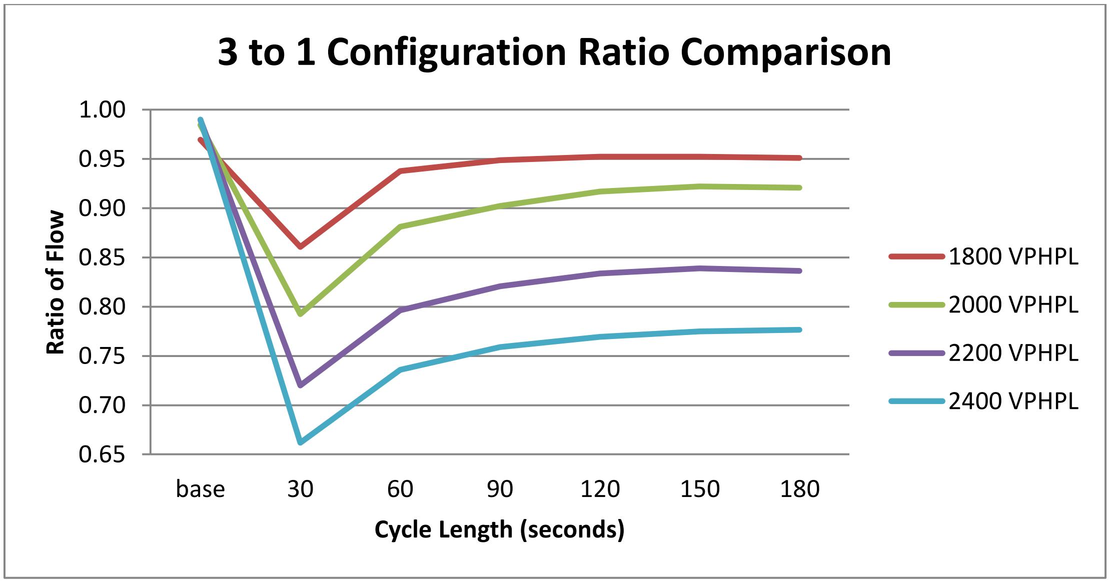



**Figure 3.3 Ratios of Input to Output Flow versus Cycle Length for 3-to-1 Lane Reduction.**

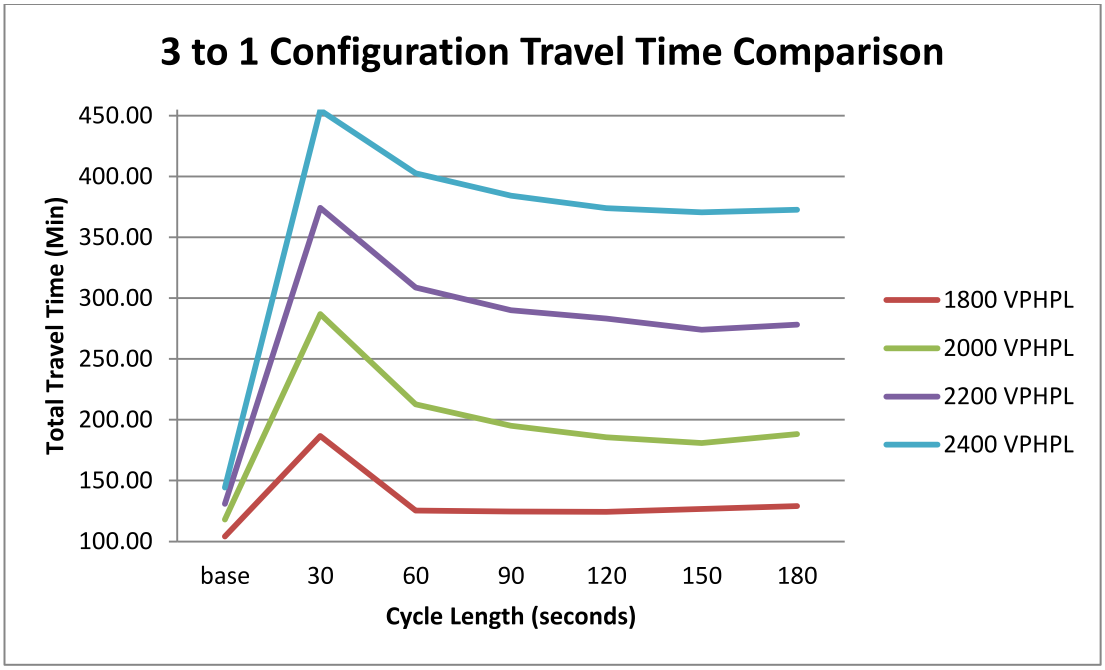



**Figure 3.4 Total Travel Time versus Cycle Length for 3 to 1 Lane Reduction.**

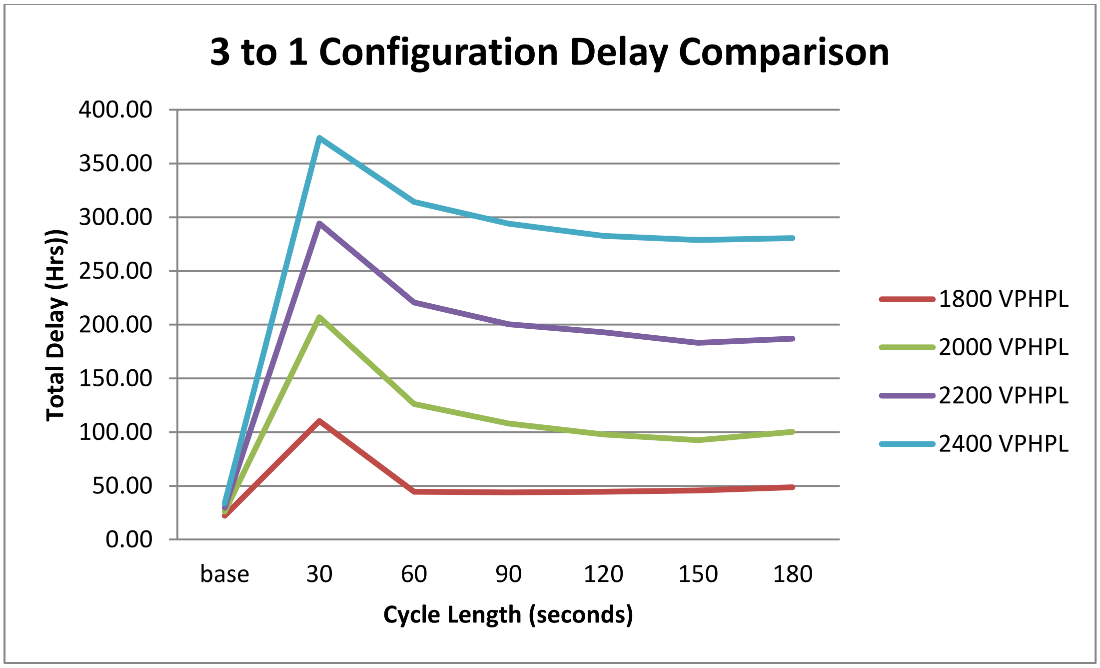



**Figure 3.5 Delay versus Cycle Length for 3 to 1 Lane Reduction.**

Table 3.1 outlines the differences among lane reduction cases. From Table 3.1, the 3 to 1 lane reduction case showed an optimal cycle length of 150 seconds for inputs of 2000, 2200, and 2400 vehicles per hour per open lane. This cycle length allowed the highest throughput, least delay, and least travel time. Cycle length effects tended to vary by only marginal amounts. For example, the ratio of flow to demand for 2400 pcphpl varied only 4% between cycles of 60 seconds and 180 seconds. Optimum cycles were determined based upon the best of the throughput, delay, and travel time criteria with equal weighting. For example, if a configuration had the lowest travel time and lowest delay, but did not have the highest ratio, it would still be considered optimum as it produced best results for 2 out of 3 criteria.

**Table 3.1 Best Cycle Lengths for Signalized Merge Cases.**

| | **1800 vphpl** | **2000 vphpl** | **2200 vphpl** | **2400 vphpl** |
|---|---|---|---|---|
| **2 to 1** | 90 – Sec | 180 - Sec | 150 – Sec | 150 – Sec |
| **3 to 1** | 90 – Sec | 150 - Sec | 150 – Sec | 150 – Sec |
| **3 to 2** | 90 – Sec | 180 - Sec | 180 – Sec | 180 – Sec |

Tables 3.2 and 3.3 represent the differences in ratios of input to output flow and vehicular delay, respectively. In all setups, there was a general reduction in throughput across the increasing cycle lengths. It appears that non-signalized merge control can handle larger through flows, but has areas of problematic merge conflicts between drivers. Once queuing developed there were zero conflicts noted with passengers trying to merge with other drivers for signalized merge, even at the tails of the queue.

**Table 3.2 Ratio of Flow Throughput to Demand Flow CORSIM.**

| | 1800 vplph | | | | | | | 2000 vplph | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Configuration | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length |
| 2-to-1 | 0.97 | 0.93 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.99 | 0.85 | 0.89 | 0.91 | 0.91 | 0.92 | 0.92 |
| 3-to-1 | 0.97 | 0.86 | 0.94 | 0.95 | 0.95 | 0.95 | 0.95 | 0.98 | 0.79 | 0.88 | 0.90 | 0.92 | 0.92 | 0.92 |
| 3-to-2 | 0.99 | 0.96 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.99 | 0.87 | 0.91 | 0.93 | 0.93 | 0.95 | 0.97 |

| | 2200 vplph | | | | | | | 2400 v vplph | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Configuration | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length |
| 2-to-1 | 0.99 | 0.72 | 0.82 | 0.84 | 0.84 | 0.85 | 0.84 | 0.99 | 0.71 | 0.75 | 0.77 | 0.77 | 0.78 | 0.77 |
| 3-to-1 | 0.99 | 0.72 | 0.80 | 0.82 | 0.83 | 0.84 | 0.84 | 0.99 | 0.62 | 0.74 | 0.76 | 0.77 | 0.77 | 0.78 |
| 3-to-2 | 0.99 | 0.79 | 0.83 | 0.84 | 0.85 | 0.86 | 0.90 | 0.99 | 0.73 | 0.76 | 0.77 | 0.77 | 0.79 | 0.83 |

**Table 3.3 Delay (seconds per vehicle) CORSIM.**

| | 1800 vplph | | | | | | | 2000 vplph | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Configuration | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length |
| 2-to-1 | 45.3 | 117.7 | 77.3 | 69.3 | 69.3 | 76.00 | 82.70 | 46.8 | 276.5 | 204.0 | 166.8 | 163.8 | 156.00 | 148.20 |
| 3-to-1 | 44.7 | 220.7 | 89.3 | 88.0 | 89.3 | 91.30 | 97.30 | 46.8 | 372.6 | 227.4 | 194.4 | 176.4 | 166.80 | 180.60 |
| 3-to-2 | 37.0 | 99.0 | 64.0 | 58.7 | 60.0 | 64.70 | 69.00 | 40.8 | 242.4 | 186.6 | 151.8 | 141.0 | 116.70 | 92.40 |

| | 2200 vplph | | | | | | | 2400 v vplph | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Configuration | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length | Baseline | 30 Sec Cycle Length | 60 Sec Cycle Length | 90 Sec Cycle Length | 120 Sec Cycle Length | 150 Sec Cycle Length | 180 Sec Cycle Length |
| 2-to-1 | 49.1 | 398.6 | 327.8 | 304.9 | 297.8 | 292.40 | 299.50 | 50.5 | 494.5 | 423.5 | 407.5 | 400.5 | 389.00 | 396.50 |
| 3-to-1 | 48.5 | 481.6 | 361.1 | 327.8 | 315.8 | 299.50 | 306.00 | 50.5 | 561.0 | 471.5 | 441.0 | 424.0 | 418.00 | 421.00 |
| 3-to-2 | 44.5 | 365.2 | 319.6 | 294.3 | 278.7 | 276.00 | 216.30 | 49.5 | 428.5 | 401.3 | 390.5 | 390.8 | 375.50 | 320.50 |

### 3.3.2 VISSIM

#### 3.3.2.1 Selection of Merge Concepts and Weighted Rating System

In order to model and simulate which merge concepts would be best applied depending on lane configuration and demand, microsimulation analysis was conducted using VISSIM software to assess performance. VISSIM is a microscopic, time-step, and behavior-based simulation model, developed to model urban traffic. As previously mentioned, this analysis is not based on any specific site and assumes no truck volume. Instead, using the Manual on Uniform Traffic Control Devices (MUTCD) from Texas and other states, the 2-to-1, 3-to-2, and 3-to-1 lane configurations were designed with volumes of 1800, 2000, 2200, 2400, and 2600 pcphpl (per open lane). Specifically, assuming a 12 foot offset and a posted speed of 55 mph, the Texas MUTCD suggests using a minimum desirable taper length of 660 feet (Texas MUTCD, 2012). In a work zone with a 3-to-1 lane closure configuration, the minimum distance between the taper from the 3-to-2 lanes and 2-to-1 lane is 1560 feet for speeds less than or equal to 65 mph, as established in various state work zone traffic control guidelines (IDOT, 2013). Thus, these minimum values were used in the simulation to develop thresholds between merge techniques.

Different lane control techniques like early merge, late merge, and signal merge can help the merging process, while also affecting queue jumping, delay, capacity, and user stress. In an effort to minimize delay, several characteristics or measures of effectiveness were analyzed from the VISSIM outputs. Delay over the entire freeway section and stopped delay provided valuable information for analysis. Specific delay characteristics that were analyzed include average delay time per vehicle in seconds and average stopped delay per vehicle in seconds. These delay outputs are a result of queue formation prior to the work zone. To assess queue formation and queue jumping, various characteristics including the average number of stops per vehicle, average queue length, maximum queue length, and number of stops within the queue were assessed. Aside from delay and queue, speed is the third and final major criterion that was analyzed using VISSIM. To assess speed as a function of changing merge concepts for different demand conditions, average speed on the entire freeway section and average speed on the link prior to the lane closure, both in miles per hour, are important characteristics. Outputs for each of these eight characteristics were obtained from simulation runs with varying lane configurations and roadway demands.

Once output results from the eight characteristics were compiled, a weighted system was developed to determine the optimal merge concept for each combination of lane configuration and user demand. Of the eight characteristic outputs used to quantify work zone traffic operations, only four provided significant trends for the signalized merge case. For signal merge, average delay time per vehicle, average number of stops per vehicle, average speed, and average stopped delay per vehicle were the only significant or useful characteristics. Thus, average speed on the link prior to the lane closure, average queue length, maximum queue length, and the number of stops within the queue produced significant outputs for early and late merge only, not signal merge. However, work zone traffic operations could be quantified by all eight characteristics for early and late merge. The weighted system was developed to help decide which merge concept technique is ideal for each lane configuration and user demand combination. This process was started by first identifying the most important evaluation characteristics and assigning 20 points to the merge concept for the output with the most efficient operations. Conclusions were made that average delay time and average speed were the most important characteristics because the effectiveness of work zone operations is dependent on delay, queue, speed, and thus, travel time. Since characteristics that quantify the queue are only applicable to early and late merge, those were not included as the most important characteristics. Additionally, average delay time and average speed quantify delay and speed over the entire freeway section, instead of assessing specific links within the section like some of the other characteristics. Also, average delay was considered more important that averaged stopped delay because it takes into account all delay that would affect traffic operations.

Average number of stops per vehicle, average stopped delay per vehicle, and average queue length were determined to be in the second tier for scoring. Thus, 10 points were awarded to the merge concept for the output with the most efficient operations. The average number of stops per vehicle and averaged stopped delay per vehicle are essential to quantifying delay, while average queue length is also in this second tier because it assesses differences between upstream demand and throughout for the entire freeway section.

In the third tier of scoring are the remaining characteristics that affect early and late merge only, including average speed on the link prior to the closure, maximum queue length, and the number of stops within the queue. These characteristics are still important when quantifying work zone traffic operations because they look at the areas of concern, located on the link prior to the work zone and within the queue. While it is important to quantify these characteristics, since they are focused on such a small area, only 5 points were awarded to the merge concept for the output with the most efficient operations. The reason that characteristics defined by queue and delay at the work zone, including maximum queue length and number of stops within the queue, were given low point values is because as demand approaches or exceeds capacity, queue length and delay become a function of observation time. The average number of stops per vehicle and average stopped delay per vehicle were also given lower point values in the weighted system because stops in the freeway system likely occur in the queue at the work zone. Since queue length and delay are functions of time as demand approaches or exceeds capacity, the validity of outputs for longer cycle lengths with higher demand could not be compromised. Thus, even though all simulation runs were one hour long, it was important that the weighted rating system would not be significantly affected by higher demand runs having longer queue lengths, especially with longer cycle lengths.

Additionally, in a real world freeway work zone situation, as the queue lengths increase, the probability of a distracted driver being in that queue also increases. This would increase the distracted driver's time headway, thus slowing down the processing rate and make time headways less uniform. Since the processing rate would be less uniform and inversely affects flow such that an increase in processing time per vehicle yields a decrease in flow, longer cycle lengths might not be ideal for managing queues. As shown in Tables 3.35 through 3.38, the cycle lengths never exceed 90 seconds and thus do not uniformly increase as demand increases.

For each test scenario, the early and late merge concepts were compared to identify the more efficient technique and weights were assigned accordingly. Then, signal merge scenarios with different cycle lengths were compared and weighted based on efficiency. Thus, signal merge with different cycle lengths of 30, 60, 90, and 120 seconds were compared to one another separately. From this, the optimal merge concept between early and late merge is compared to the optimal signal merge, with varying cycle lengths, to determine the overall ideal merge concept by reweighting against the overall more efficient output for each characteristic.

#### 3.3.2.2 Introduction to Early Merge in VISSIM

The early merge control technique is used to warn drivers in advance of a work zone of an upcoming closed lane(s). The typical layout of the early merge strategy involves lane closure signage 1.5 miles in advance of the transition area, which is depicted in Figure 3.6. The signs are followed by a lane reduction sign about 1,500 feet from the entrance to the transition area (Idewu, 2011).

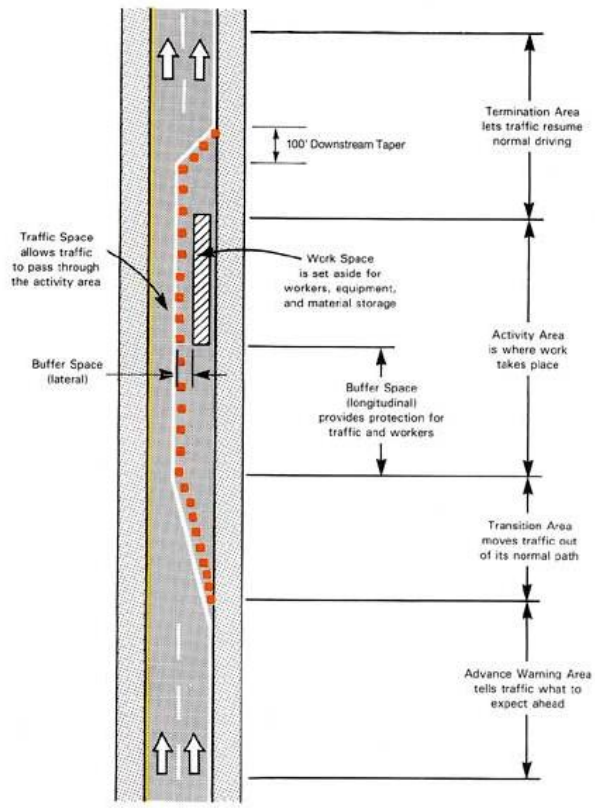



**Figure 3.6 Depiction of the Components Parts of a Temporary Work Zone (MUTCD, n.d.).**

The early merge technique was modeled in VISSIM using various closure lengths prior to the work zone, up to one-quarter mile. One-quarter mile is assumed to be ample distance for an early merge because the distance should be long enough where users cannot perceive the work zone upstream. If the distance is long enough for users to not perceive the work zone, then there would be minimal distractions as a result of the work zone and the merging process can function efficiently. Closure prior to the work zone allows time for the user to find a gap to merge and complete this merging process prior to the lane closure(s). Thus, early merge reduces the capacity of the roadway, but if used properly in conditions with low demand, can minimize queue jumping and user stress. In agreement with this hypothesis is research completed by Yang, which suggests that this technique is very effective if traffic demand is low compared to capacity. However, the system breaks down when the demand is high because vehicles have fewer gaps in which to merge (Yang, 2009). Therefore, VISSIM is applied to determine the lower demand thresholds that can use the early merge technique for various lane configurations.

#### 3.3.2.3 Differing Applications of Early Merge Using VISSIM

In order to determine which merge concepts can best be applied based on freeway configuration and demand, it is also important to determine the most useful application of the early merge concept. The early merge concept was tested at various closure lengths, including one link, two links, and three links closed prior to the late merge or work zone area. The first two links are each approximately one-sixteenth mile long. Therefore, in the case of early merge with two links closed, the closure length was about one-eighth mile or half the distance of early merge with three links closed. From the VISSIM outputs, as fewer links prior to the work zone are closed, the freeway system behaves more like the late merge technique. Thus, three links closed prior to the work zone yields results unlike the late merge technique. In Table 3.4, the ideal early merge concept for the 3-to-2 configuration with 2000 pcphpl is the early merge with three links closed. Specifically, the average delay time per vehicle, average number of stops per vehicle, average stopped delay per vehicle, average queue length, maximum queue length, and number of stops within the queue are the smallest for early merge with three links closed, when compared to the various early merge closure lengths and late merge. Additionally, the average overall speed and average speed on the link prior to the lane closure is largest for early merge with three links closed, when compared to the various early merge closure lengths and late merge. It is less important that early merge with three links closed is ideal in this situation; rather, these outputs show the trend that early merge with a smaller number of links closed behaves more like the late merge technique. Therefore, early merge with three links closed, referred to in future tables as just early merge, provides a representation that is unique from the late merge concept.

**Table 3.4 VISSIM Outputs of Varying Lengths of the Early Merge for 3-to-2 Configuration and 2000 pcphpl.**

| 3 to 2 Configuration: 2000 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| **Early Merge (3 links closed, 1/4 mile)** | **3.463** | **0.000333** | **62.534** | **0.003** | **62.739** | **0** | **35.667** | **3** |
| Early Merge (2 links closed) | 3.553 | 0.001 | 62.51 | 0.007 | 61.091 | 0.333 | 49 | 4.667 |
| Early Merge (1 link closed) | 4.323 | 0.0037 | 62.32 | 0.02 | 51.909 | 2 | 114.667 | 25 |
| Late Merge | 16.686 | 0.033 | 59.711 | 0.283 | 37.649 | 18.667 | 203.667 | 131.667 |

### 3.3.2.4 Introduction to Late Merge in VISSIM

Unlike early merge, late merge is a technique that encourages all lanes to be used until a specified merging point. Once vehicles reach this point, users in the closed lane(s) merge with those in the open lane(s) in an alternating pattern (Idewu, 2009). Thus, late merge tries to take advantage of the full capacity of the freeway approaching the work zone to minimize the length of queue. VISSIM is used to test the application of the late merge technique, as one that can be used in cases with low to moderate traffic demand and therefore, can be used more efficiently than early merge in cases with greater demand. In VISSIM, the late merge technique is applied by keeping all lanes open up until the work zone area and measuring various criteria that show the effectiveness of this technique.

As discussed in Chapter 2.1, both early merge and late merge can be implemented as either static or dynamic, where static uses signage that displays a single message in the same location at all times, regardless of traffic conditions. Dynamic merge concepts involve real-time control measures to determine which signage should be used upstream to inform approaching drivers of the upcoming conditions. Using VISSIM simulation, both early and late merge were implemented using static signage.

### 3.3.2.5 Introduction to Joint Merge

Although not extensively used or explored, joint merge could present an interesting technique to bridge early and late merge. The joint merge technique uses signage in the advance warning area and channeling devices in the transition zone, to help create a balanced distribution of vehicles in each lane (Idewu, 2009). The advance warning area and transition zone can be found in Figure 3.6. Thus, using various warning signs and a "funnel-shaped" configuration, the joint merge can simultaneously merge two lanes into one more naturally than late merge. Further researchers should consider possible applications of joint merge using VISSIM.

#### 3.3.2.6 Introduction to Signalized Merge in VISSIM

Aside from early merge, late merge, and possible future applications of joint merge, the signal merge technique can be used at work zones to facilitate safe, orderly traffic movement. Essentially, signalized control on freeways was developed to manage merging when the work zone area is heavily congested. Much like early and late merge, VISSIM is used to determine the threshold for this merge concept and try to numerically assign a value to the term "heavily congested." In VISSIM for signal merge, using lane configuration and driving behavior parameters, vehicles were forced to drive up to the signal merge and thus, mimic the late merge concept. Fixed cycle lengths of 30, 60, 90, and 120 seconds are used on 2-to-1, 3-to-2, and 3-to-1 lane configurations.

On green, the vehicles can freely move into the open lane as vehicles in the other lane will be stopped for the red signal. The cycle length was split equally between all lanes, assuming an equal distribution of vehicular demand in each lane. In the case of the 2-to-1 configuration, the cycle lengths were split equally between both lanes. For the 3-to-2 and 3-to-1 configurations however, equal fractions of green time are provided to the closed lane and the through lanes. Assuming the lane closures occur on the left side of the freeway section, the far left lane would close for both the 3-to-1 and 3-to-2 configuration, with an additional lane closure in the 3-to-1 case at a minimum distance between tapers of 1560 feet. In both configurations, split signal timing is used since traffic in two lanes can move concurrently, with green provided to the far left lane to merge, followed by equal fraction of green time for the other two through lanes. Thus, the signal merge technique has the capabilities to minimize queue jumping because of the equal fractions of green time for all lanes. Equal fractions of green time provided for all lanes, assuming essentially equal queues in all lanes, would likely deter users from queue jumping because there would be minimal space for queue jumping and no benefit to moving into another lane. This equal fraction of green time for each phase and thus all lanes is depicted in Figure 3.7. Lanes 1 and 2 are the through lanes that will remain open when merging from 3-to-2 lanes, prior to the merge from 2-to-1 lane. Thus, these two through lanes have the same amount of green time as lane 3, which is the lane that is merging into the two through lanes before the second lane closure.

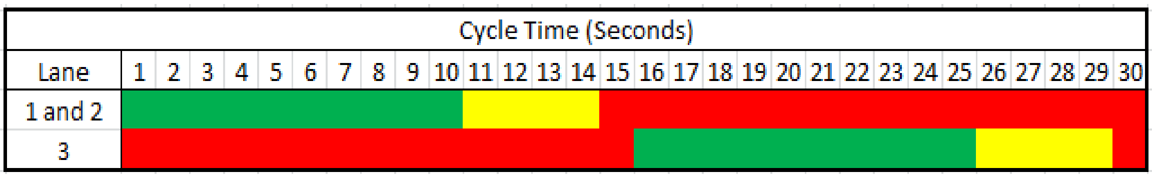



**Figure 3.7 Signal Time Allocation for 3-to-1 Lane Configuration with 30 Second Cycle.**

Based on the Greenshield's Traffic Flow Model and traditional belief among practitioners, others anticipate that longer cycle lengths would maximize throughput flow and reduce delay the most. The results presented in this analysis are generally consistent with the VISSIM results and my assumptions, but inconsistent with the aforementioned practitioners. Greenshield's Traffic Flow Model assumes that in each cycle, time headways between consecutive vehicles decrease after the first five vehicles have been served into the green time, due to the phase-change lost time diminishing as a percentage of the cycle length. Thus, the common practice is to use longer cycle lengths to increase capacity based on the assumption that saturation flow remains constant once the initial lost time has been accommodated.

In 2008, the Federal Highway Administration (FHWA) conducted a study to provide guidance on effective strategies to alleviate the traffic congestion at signalized intersections and results were published in a Richard W. Denney Jr. article by the Transportation Research Board. Denney conducted a study to investigate the impacts of long green times and cycles at congested traffic signals. The research focused on whether headways increased with long green times and if throughput increased as cycle length increased. The results showed that headways increased with long green times, as a result of departing turning vehicles. As a result, this effect could cause a significant increase in overall average approach headways (Denney, 2009). The results also showed that maximum throughput did not increase with longer cycles. With values derived from the field data, increasing the cycle did not increase throughput. In simulation, increasing the cycle length caused a reduction in throughput, as a result of increasing the effect of departing turning traffic on the average headway (Denney, 2009).

Two reasons to explain these observations were hypothesized. First, during the red signal interval, vehicles who intend to turn at the intersection are trapped in a long queue in the through lanes. These vehicles would maneuver from through lanes to the appropriate lanes to turn during the through movement green interval, thus lowering the flow on the through lanes (Denney, 2009). Second, it may be that drivers respond to brake lights of the vehicle in front rather than the green light because their position in the queue is too far to clearly see the signal (Denney, 2009). In such cases, their perception–reaction time may not overlap with vehicles in front of them, as characterized originally by Greenshield’s Model. After analyzing the field data, the authors show that headways in lanes adjacent to turning lanes significantly increased and stop line flow rates reduced when the queue cleared to the upstream end of the turning lane. This finding suggests that maximum throughput is served when green times use the ability to feed the stop line with maximum flow. The simulation results of this study also indicate that larger percentages of green that can be used by flows unaffected by turning traffic causes higher throughput.

The paper concluded that by keeping the green time down to the point where only the queue to the upstream end of a 500-ft turn lane was served in each cycle, flow at the stop line is maintained close to ideal saturation and the overall throughput does not decrease. It was concluded, therefore, that the common belief that longer cycle lengths can be assumed to result in greater capacity cannot be supported by the behavior at this intersection (Denney, 2009).

#### 3.3.2.7 VISSIM Outputs for 2-to-1 Lane Configuration

The first case that was modeled is the 2-to-1 lane configuration with a vehicle demand of 1800 pcphpl shown in Table 3.5, and the most efficient traffic operations for each characteristic are shown in bold. From the VISSIM outputs, the early merge and late merge techniques were initially compared, using various measures of delay, stops, speed, and queue length. The comparison between these two techniques on all measures shows favorable results for using the early merge technique, as highlighted in yellow. The outputs of four different signalized merge applications of 30, 60, 90, and 120 second cycle lengths were then compared, using measures similar to the early and late merge comparison. As previously discussed, average speed on the link prior to the closure, average queue length, maximum queue length, and number of stops within the queue did not provide any applicable evidence that is not already shown in the previous measures. Of the four different cycle lengths, 60 seconds is ideal using the weighted system essentially because it minimizes the average delay time per vehicle and average stopped delay per vehicle, while maximizing the average speed. Since average delay time per vehicle and average speed has the highest allotment of points with 20 and the outputs for other characteristics are also the most efficient values or not far from them, it is clear that the 60 second cycle length ideal for this signal merge case. After it was determined that early merge and signal merge with a 60 second cycle length were the most efficient merge concepts for traffic operations in their first comparison group, these two merge concepts were compared to one another. While still using the overall most efficient outputs as the baseline for reweighting, early merge was determined to be the ideal approach when comparing all types of merge concepts. The outputs from the weighted decision-making process for 2-to-1 lane configuration with 1800 pcphpl can be found in Table 3.6.

**Table 3.5 VISSIM Outputs for 2-to-1 Lane Configuration and 1800 pcphpl.**

| 2 to 1 Configuration: 1800 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **4.752** | **0.013** | **61.517** | **0.183** | **44.447** | **3.333** | **103.333** | **24** |
| Late Merge | 5.766 | 0.036 | 61.292 | 0.46 | 37.567 | 14 | 268.333 | 71.667 |
| Signal Merge-30 s | 198.982 | 2.236 | 34.979 | 9.242 | | | | |
| Signal Merge-60 s | 25.782 | 0.672 | 56.926 | 8.224 | | | | |
| Signal Merge-90s | 27.466 | 0.616 | 56.584 | 11.382 | | | | |
| Signal Merge-120s | 32.749 | 0.645 | 55.549 | 16.167 | | | | |

**Table 3.6 Weighted Process to Determine Ideal Merge Concept for 2-to-1 Lane Configuration and 1800 pcphpl.**

| Weighted Decision-making for 2-to-1 Lane Configuration with 1800 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 85 | LM | 54.206 | | | | |
| SM30s | 26.534 | SM60s | 59.167 | SM90s | 39.866 | SM120s | 37.445 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| EM | 60 | | | | | | |
| SM60s | 22.61 | | | | | | |

The second VISSIM simulation involved a 2-to-1 lane configuration and 2000 pcphpl. The comparisons between early merge and late merge showed that for all measures except maximum queue length, early merge would be ideal for this configuration and user demand. As shown in Table 3.7, the maximum queue length for early merge is 382.7 feet, which is slightly greater than the maximum queue length for late merge of 335 ft. This is relatively insignificant because the average queue length for early merge is significantly less than for late merge. Additionally, the average delay time per vehicle for early merge is less than one-fourth that of late merge. Using the weighted system, the optimal signal merge cycle time for three of the four measures is 120 seconds, even though the output of the average stopped delay per vehicle is the less efficient for traffic operations. However, by extending cycle lengths and green time to 120 second cycles, issues with delaying users at the opposing red light and not increasing throughput (Denney, 2009) a 120 second cycle length is problematic. Since VISSIM cannot model the actual reactions of drivers queue jumping, for instance, for long delays at a signal, early merge should be used as the ideal merge concept. Regardless of this issue, the weighted system shows that early merge is the ideal merge concept when compared to signal merge with 120 second cycle lengths. The outputs from the weighted decision-making process for 2-to-1 lane configuration with 2000 pcphpl can be found in Table 3.8.

**Table 3.7 VISSIM Outputs for 2-to-1 Configuration and 2000 pcphpl.**

| 2 to 1 Configuration: 2000 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **9.463** | **0.058** | **60.402** | **1.194** | **29.958** | **30.333** | 382.67 | **110** |
| Late Merge | 42.731 | 0.466 | 54.87 | 4.64 | 21.84 | 78 | **335** | 299 |
| Signal Merge-30 s | 375.207 | 3.034 | 24.658 | 11.45 | | | | |
| Signal Merge-60 s | 75.41 | 1.535 | 48.348 | 15.269 | | | | |
| Signal Merge-90s | 59.588 | 5.159 | 50.799 | 21.039 | | | | |
| Signal Merge-120s | 57.336 | 1.069 | 51.16 | 27.792 | | | | |

**Table 3.8 Weighted Process to Determine Ideal Merge Concept for 2-to-1 Lane Configuration and 2000 pcphpl.**

| Weighted Decision-making for 2-to-1 Lane Configuration with 2000 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 84.377 | LM | 40.789 | | | | |
| SM30s | 26.219 | SM60s | 46.565 | SM90s | 48.745 | SM120s | 54.12 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM120s | 21.213 | | | | | | |

The VISSIM outputs for the 2-to-1 lane configuration with 2200 pcphpl are shown in Table 3.9. The early merge technique yields less average delay time per vehicle, average number of stops per vehicle, and average stopped delay per vehicle, when compared to late merge. Early merge also provides a greater average speed than late merge, but the concern with early merge is queue development. Since these merge concepts are applied just prior to the work zone, average speed on the link prior to the closure is significant because this helps represent the level of congestion as a result of the merge. While the concerns of queue development are important considerations, the weighted system places the greatest emphasis on average delay time per vehicle and average speed. Thus, the weighted process to determine the ideal merge concept between early and late merge yielded increasingly similar scores, but early merge was more efficient.

When first looking at the VISSIM outputs, the initial thought was that signal merge with a 90 second cycle length would be best for signal merge because the two characteristics with the highest point weight appear with 90 second cycle lengths. However, the benefit of the weighted method to determine the ideal merge concept is that it accounts for how far each output value is from outputs with the most efficient operations. Thus, signal merge with a 60 second cycle length is near the 90 second cycle length for both characteristics for which the 90 second case is ideal. Although the average stopped delay per vehicle does not have the highest weighted point value, the 90 second cycle length has approximately 32.9 seconds of averaged stopped delay, compared to 19.5 seconds for the 60 second cycle length. This significant difference in deviation from the most efficient 12.8 seconds of average stopped delay per vehicle for the 30 second cycle length likely was the determining factor in the 60 second cycle length being most efficient. After reweighting and comparing early merge to signal merge with 60 second cycle lengths, similar reasoning suggested that the signal merge with a 60 second cycle length was the ideal merge concept. The outputs from the weighted decision-making process for 2-to-1 lane configuration with 2200 pcphpl can be found in Table 3.10.

**Table 3.9 VISSIM Outputs for 2-to-1 Configuration and 2200 pcphpl.**

| 2 to 1 Configuration: 2200 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | 224.967 | **3.102** | 33.056 | 62.051 | 12.208 | 339.333 | 515 | 530.333 |
| Late Merge | 268.389 | 4.137 | 30.038 | 89.319 | **13.704** | **249.667** | **365** | **411.333** |
| Signal Merge-30 s | 569.251 | 3.867 | 17.922 | **12.773** | | | | |
| Signal Merge-60 s | 240.116 | 3.377 | 31.945 | 19.483 | | | | |
| Signal Merge-90s | **214.942** | 4.021 | **33.728** | 32.966 | | | | |
| Signal Merge-120s | 223.159 | 4.486 | 33.138 | 47.713 | | | | |

**Table 3.10 Weighted Process to Determine Ideal Merge Concept for 2-to-1 Lane Configuration and 2200 pcphpl.**

| Weighted Decision-making for 2-to-1 Lane Configuration with 2200 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 79.234 | LM | 74.384 | | | | |
| SM30s | 46.912 | SM60s | 53.402 | SM90s | 52.273 | SM120s | 49.119 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| EM | 53.14 | | | | | | |
| **SM60s** | **57.252** | | | | | | |

Unlike the smaller user demands, the 2400 pcphpl outputs in Table 3.11 led to the conclusion late merge is better when compared to early merge because of the ability of late merge to minimize the queue by taking advantage of all available freeway capacity. Results from the weighted system indicate that late merge was slightly more efficient than early merge, with 78.7 points for late merge and 78.2 points for early merge. This suggests that as demand increases and exceeds capacity, late merge is more efficient than early merge, since the points for late merge increased as demand increased from 1800 to 2400 pcphpl. Although the interpretation that late merge is more appropriate than signal merge with a 90 second cycle length can be made, most of the output values are comparable except for one. The average stopped delay per vehicle for late merge of 223.9 seconds is more than six times greater than the 90 second cycle length signal merge value of 36.6 seconds. This is likely one of the primary reasons why the ideal merge concept for this case is signal merge with a 90 second cycle length using the weighted system.

The outputs from the weighted decision-making process for the 2-to1 lane configuration with 2400 pcphpl can be found in Table 3.12.

**Table 3.11 VISSIM Outputs for 2-to-1 Configuration and 2400 pcphpl.**

| 2 to 1 Configuration: 2400 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | 359.349 | 4.792 | **25.132** | 195.822 | 20.687 | 471.333 | 515 | 202 |
| Late Merge | 418.524 | **4.598** | 22.768 | 233.908 | **21.629** | **316.333** | **365** | **142.333** |
| Signal Merge-30 s | 751.98 | 5.278 | 14.046 | **15.425** | | | | |
| Signal Merge-60 s | 431.7 | 5.109 | 22.166 | 21.122 | | | | |
| Signal Merge-90s | **333.09** | 6.498 | 23.683 | 36.564 | | | | |
| Signal Merge-120s | 405.1 | 7.602 | 23.214 | 56.058 | | | | |

**Table 3.12 Weighted Process to Determine Ideal Merge Concept for 2-to-1 Lane Configuration and 2400 pcphpl.**

| Weighted Decision-making for 2-to-1 Lane Configuration with 2400 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 78.156 | LM | 78.663 | | | | |
| SM30s | 40.4 | SM60s | 51.453 | SM90s | 53.639 | SM120s | 45.521 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| LM | 46.708 | | | | | | |
| SM90s | 57.076 | | | | | | |

At first, it seems that similar conclusion can be drawn from Table 3.13 for a demand of 2600 pcphpl as the 2400 pcphpl demand case because late merge is the most efficient for the same characteristics. However, as a result of the point selection process and weighted system, early merge was actually the ideal merge concept when compared to late merge. This result though, is likely a fluke because as demand increases, late merge should allow for more efficient traffic operations because it allows users to take advantage of the full capacity of the freeway approaching a work zone be keeping the closed lane open longer. The signal merge comparisons suggested the 60 second cycle lengths would be the most efficient for traffic operations, even though the highest weighted characteristics were optimal for signal merge with 90 second cycle lengths. Thus, this suggests that the weighted system may have artificially affected the optimal signal merge concept score.

While the 60 second cycle length was maintained in this level of the analysis, the 90 second cycle length was used when discussing overall trends because the cycle length should not decrease as user demand increases. This decrease was likely a fluke, as a result of the weighted scoring system. The weighted system for the 2-to-1 lane configuration with 2600 pcphpl can be found in Table 3.14.

**Table 3.13 VISSIM Outputs for 2-to-1 Configuration and 2600 pcphpl.**

| 2 to 1 Configuration: 2600 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **484.35** | 5.76 | **20.195** | 206.06 | 21.182 | 485 | 515 | 156.67 |
| Late Merge | 560.77 | **5.662** | 18.004 | 294.33 | **29.852** | **354.33** | **365** | **31.667** |
| Signal Merge-30 s | 882.07 | 6.425 | 12.345 | **18.233** | | | | |
| Signal Merge-60 s | 594.34 | 6.393 | 17.178 | 21.821 | | | | |
| Signal Merge-90s | 572.88 | 8.105 | 17.686 | 38.584 | | | | |
| Signal Merge-120s | 573.83 | 9.175 | 17.658 | 56.876 | | | | |

**Table 3.14 Weighted Process to Determine Ideal Merge Concept for 2-to-1 Lane Configuration and 2600 pcphpl.**

| Weighted Decision-making for 2-to-1 Lane Configuration with 2600 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 59.83 | LM | 52.106 | | | | |
| SM30s | 46.9 | SM60s | 57.059 | SM90s | 52.613 | SM120s | 50.109 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| EM | 50.106 | | | | | | |
| **SM60s** | **52.321** | | | | | | |

### 3.3.2.8 VISSIM Outputs for 3-to-2 Lane Configuration

The VISSIM outputs for the 3-to-2 lane configuration and 1800 pcphpl provide support for early merge as the ideal merge concept technique. For each measure, early merge is more efficient in managing the traffic flow than late merge and all forms of signal merge, as shown in Table 3.15. The 60 second cycle length would be optimal among the signal merge scenarios because even when it is not most efficient for a specific measure, it is very near optimal in every measure. For example, although the 90 second signal merge has the optimum average delay time per vehicle, the 60 second cycle length is relatively close to the minimum, unlike the 30 second cycle length. Additionally, the average stopped delay per vehicle reaches a minimum value of 20.4 seconds for the 30 second cycle length, but the 60 second cycle length is nearly the same, unlike the 90 and 120 second cycle lengths. Regardless, from the analysis of each measure, early merge would be the most efficient merge technique for this configuration and user demand, as shown in Table 3.16.

**Table 3.15 VISSIM Outputs for 3-to-2 Configuration and 1800 pcphpl.**

| 3 to 2 Configuration: 1800 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **3.018** | **0.0003** | **62.669** | **0.002** | **63.423** | **0** | **26.667** | **1.333** |
| Late Merge | 3.296 | 0.002 | 62.591 | 0.0117 | 53.944 | 0.667 | 76 | 11.667 |
| Signal Merge-30 s | 809.46 | 6.994 | 13.222 | 20.371 | | | | |
| Signal Merge-60 s | 444.18 | 5.311 | 21.728 | 21.642 | | | | |
| Signal Merge-90s | 416.65 | 6.889 | 22.786 | 38.557 | | | | |
| Signal Merge-120s | 416.76 | 7.857 | 22.798 | 57.435 | | | | |

**Table 3.16 Weighted Process to Determine Ideal Merge Concept for 3-to-2 Lane Configuration and 1800 pcphpl.**

| Weighted Decision-making for 3-to-2 Lane Configuration with 1800 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 85 | LM | 48.076 | | | | |
| SM30s | 39.487 | SM60s | 57.234 | SM90s | 52.981 | SM120s | 50.301 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM60s | 7.072 | | | | | | |

The general trends from the VISSIM outputs in the 1800 pcphpl case are applicable to the 2000 pcphpl simulation. In Table 3.17, all measures suggest that early merge is more efficient than late merge. Similar to the approach taken with the 1800 pcphpl demand, even though signal merge with a 60 second cycle length is not the most efficient technique for all measures, it does not deviate far from those values. For instance, even though 15.8 mph is not the optimum average speed, it is close to that ideal value of 16.4 mph for the 120 second cycle length. However, the average stopped delay per vehicle for the 120 second cycle length deviates far from the optimum value for the 60 second cycle length. Thus, early merge is overall the most efficient merge concept technique and the 60 second cycle length is the optimum signal merge concept. As shown in Table 3.18, early merge is the most efficient merge concept for a 3-to-2 lane configuration and a user demand of 2000 pcphpl.

**Table 3.17 VISSIM Outputs for 3-to-2 Configuration and 2000 pcphpl.**

| 3 to 2 Configuration: 2000 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **3.463** | **0.0003** | **62.534** | **0.003** | **62.739** | **0** | **35.667** | **3** |
| Late Merge | 16.686 | 0.033 | 59.711 | 0.283 | 37.649 | 18.667 | 203.667 | 131.667 |
| Signal Merge-30 s | 958.77 | 8.608 | 11.53 | 25.027 | | | | |
| Signal Merge-60 s | 666.8 | 7.363 | 15.797 | 23.935 | | | | |
| Signal Merge-90s | 641.3 | 9.511 | 16.284 | 43.075 | | | | |
| Signal Merge-120s | 639.63 | 10.624 | 16.358 | 64.043 | | | | |

**Table 3.18 Weighted Process to Determine Ideal Merge Concept for 3-to-2 Lane Configuration and 2000 pcphpl.**

| Weighted Decision-making for 3-to-2 Lane Configuration with 2000 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 85 | LM | 27.435 | | | | |
| SM30s | 45.557 | SM60s | 58.499 | SM90s | 53.156 | SM120s | 50.668 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM60s | 5.158 | | | | | | |

The same trends experienced with a user demand of 2000 pcphpl were found with 2200 pcphpl, as shown in Table 3.19. For all characteristics, early merge was most efficient, when compared to late merge and all cycle lengths of signal merge. Thus, as shown by the bold values, the weighted system was not needed to determine the ideal merge concept because early merge was most efficient in all cases. To determine the optimum signal merge technique, the weighted system was needed. While signal merge with 60 and 120 second cycle lengths were each best for two characteristics, the 60 second cycle length did not deviate far from the optimum when it was not best. Conversely, as shown by the average stopped delay per vehicle, signal merge with a 60 second cycle length yielded 25.6 seconds of delay, while 120 second cycle lengths produced 70.4 seconds of delay on average. Table 3.20 shows the weighted decision-making system to determine the ideal merge concept for a 3-to-2 lane configuration with 2200 pcphpl.

**Table 3.19 VISSIM Outputs for 3-to-2 Configuration and 2200 pcphpl.**

| 3 to 2 Configuration: 2200 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **4.07** | **0.001** | **62.362** | **0.008** | **61.756** | **0.667** | **50.333** | **3.667** |
| Late Merge | 139.048 | 0.349 | 43.713 | 6.415 | 25.759 | 47.333 | 279 | 216.667 |
| Signal Merge-30 s | 1048.67 | 9.602 | 10.707 | 26.791 | | | | |
| Signal Merge-60 s | 786.523 | 8.496 | 13.919 | 25.545 | | | | |
| Signal Merge-90s | 770.464 | 11.009 | 14.166 | 46.937 | | | | |
| Signal Merge-120s | 770.45 | 12.34 | 14.183 | 70.382 | | | | |

**Table 3.20 Weighted Process to Determine Ideal Merge Concept for 3-to-2 Lane Configuration and 2200 pcphpl.**

| Weighted Decision-making for 3-to-2 Lane Configuration with 2200 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 85 | LM | 14.646 | | | | |
| SM30s | 48.462 | SM60s | 59.219 | SM90s | 53.135 | SM120s | 50.514 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM60s | 4.572 | | | | | | |

The VISSIM outputs for 3-to-2 configuration and 2400 pcphpl demand in Table 3.21 suggest a continuation of a trend that was not expected. Although early merge is the optimal merge concept for 1800, 2000, and 2000 pcphpl for the same configuration, the expectation was that early merge would likely be best if traffic demand is low compared to capacity. While the VISSIM software does not provide a user level capacity specification capability, the Highway Capacity Manual typically suggests that freeway lane capacities range from 1800 to around 2300 pcphpl ("Guide for Highway," 2013). Lane capacities in work zones are certainly less than ideal conditions so early merge would be best for demands less than 2300 pcphpl. However, the VISSIM output suggests that early merge is still optimal when compared to late merge because it is statistically better than late merge in all measures, aside from maximum queue length. One possible reason for this discrepancy is that with higher demand, lanes are more congested. In reality, this congestion increases the likelihood for queue jumping, driving in the closed lane(s), and other dangerous actions; however, VISSIM cannot simulate these actions. Using the weighted system, signal merge with a 60 second cycle length is the optimal signal merge technique. After comparing the early merge to the signal merge with 60 second cyle lengths, the outputs suggest that early merge should be the best merge concept as shown in Table 3.22, but using the rationale described above, signal merge with 60 second cycle lengths is suggested.

**Table 3.21 VISSIM Outputs for 3-to-2 Configuration and 2400 pcphpl.**

| 3 to 2 Configuration: 2400 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **222.628** | **0.481** | **35.578** | **1.452** | **17.078** | **53.667** | 515 | **252** |
| Late Merge | 319.729 | 0.623 | 26.975 | 6.873 | 13.751 | 55 | **364.667** | 293.333 |
| Signal Merge-30 s | 1102.3 | 9.631 | 10.273 | 26.031 | | | | |
| Signal Merge-60 s | 860.086 | 9.212 | 12.969 | 26.629 | | | | |
| Signal Merge-90s | 839.852 | 11.935 | 13.234 | 48.946 | | | | |
| Signal Merge-120s | 836.861 | 13.054 | 13.298 | 72.507 | | | | |

**Table 3.22 Weighted Process to Determine Ideal Merge Concept for 3-to-2 Lane Configuration and 2400 pcphpl.**

| Weighted Decision-making for 3-to-2 Lane Configuration with 2400 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 83.54 | LM | 63.529 | | | | |
| SM30s | 54.254 | SM60s | 58.736 | SM90s | 52.869 | SM120s | 50.647 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM60s | 13.535 | | | | | | |

The VISSIM outputs for the 3-to-2 lane configuration with 2600 pcphpl, as shown in Table 3.23, have similar trends to the outputs from the 2400 pcphpl case for early and late merge, at least in the first four measures. This again suggests that as a result of a demand increase to 2600 pcphpl, congestion would increase the possibility of queue jumping, driving in the closed freeway lanes, and other dangerous actions. These actions cannot be modeled by VISSIM so they are neglected in the statistical comparisons and may be the cause of early merge appearing to be best when compared to late merge. One key change with the 2600 pcphpl demand case is that the values for the first four characteristics are not significantly different from one another when comparing early and late merge. The average delay time per vehicle, average number of stops per vehicle, and average speed are comparable. In addition, the average speed on the link prior to the closure is greater for late merge at 14.7 mph, compared to 13.9 mph for early merge. Furthermore, the maximum queue length is significantly greater for early merge than late merge. For these reasons, late merge seems more efficient in managing traffic when compared to late merge. Signal merge with a 120 second cycle length is the optimal merge concept because of the ability to keep traffic moving. While the average stopped delay per vehicle and average number of stops per vehicle are not the smallest for signal merge with a 120 second cycle length, the average speed, and 49.6 mph is more than double the speed for any other technique. Although Table 3.24 shows that early merge and signal merge with 120 second cycle lengths are the two best choices, there seems to be a serious flaw. While it makes sense that signal merge with 120 second cycle lengths would provide the highest average speed because it minimizes speed lost waiting at the signal by extending green times, it is concerning that that stopped delay does not have more of a negative effect. Since long cycle lengths cause delay issues and increase the probability of drivers getting frustrated with having to wait through long red signal times, the 60 second cycle length was chosen as the best for a 3-to-2 lane configuration and 2600 pcphpl, despite the weighted calculations in Table 3.24. Due to the inability of VISSIM to model queue jumping and dangerous driving behavior in early merge, as well as Denney's findings about long cycle lengths not increasing throughput with 120 second cycle lengths, the 60 second cycle length is recommended as the choice. This recommendation is reflected in the summary merge recommendations of Tables 3.35 and 3.36.

**Table 3.23 VISSIM Outputs for 3-to-2 Configuration and 2600 pcphpl.**

| 3 to 2 Configuration: 2600 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **439.994** | **0.901** | 22.062 | **4.373** | 13.871 | **60.667** | 515 | 279 |
| Late Merge | 458.967 | 1.354 | 21.522 | 22.794 | **14.727** | 94.333 | **365** | **260** |
| Signal Merge-30 s | 1143.25 | 10.395 | 9.961 | 28.867 | | | | |
| Signal Merge-60 s | 902.687 | 9.66 | 12.476 | 27.35 | | | | |
| Signal Merge-90s | 886.219 | 12.357 | 12.687 | 38.584 | | | | |
| Signal Merge-120s | 882.516 | 13.506 | **49.554** | 74.709 | | | | |

**Table 3.24 Weighted Process to Determine Ideal Merge Concept for 3-to-2 Lane Configuration and 2600 pcphpl.**

| Weighted Decision-making for 3-to-2 Lane Configuration with 2600 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 82.912 | LM | 68.688 | | | | |
| SM30s | 38.226 | SM60s | 44.588 | SM90s | 39.943 | SM120s | 50.813 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **48.904** | | | | | | |
| SM120s | 31.224 | | | | | | |

### 3.3.2.9 VISSIM Outputs for 3-to-1 Lane Configuration

The VISSIM outputs for a 3-to-1 lane configuration with user demands of 1800, 2000, 2200 pcphpl, as shown in Tables 3.25 through 3.30, respectively, provide similar results to each other. In all three simulations, early merge and 60 second cycle length signal merge are the optimal merge techniques because both minimize delay and maximize speed in almost all measures, through the initial comparisons. By comparing early merge to the 60 second cycle length signal merge, early merge provides optimum travel conditions in all measures. Additionally, the 2200 pcphpl user demand provides evidence for early merge because it not only minimizes delay and maximizes speed, but also minimizes queue lengths. Initially, it was concerning that early merge minimized queues better than late merge because late merge typically takes full advantage of roadway capacity. While the queue was minimized in through lanes at the merge, the delay was experienced primarily by the merging lane. This also suggests that the demand is small enough that users were able to find enough gaps at the early merge to prevent queuing. From all the outputs though, early merge and signal merge with a 60 second cycle length are ideal and early merge is the optimum overall merge concept. The weighted system that shows the numerical values for efficiency of each merge concept with a 3-to-2 lane configuration and 1800, 2000, and 2200 pcphpl are shown in Tables 3.26, 3.28, and 3.30, respectively.

**Table 3.25 VISSIM Outputs for 3-to-1 Configuration and 1800 pcphpl.**

| 3 to 1 Configuration: 1800 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **2.175** | **0.0047** | **65.457** | 0.0903 | **66.449** | 0 | 0 | 0 |
| Late Merge | 2.246 | 0.0053 | 65.445 | **0.09** | 66.272 | 0 | 0 | 0 |
| Signal Merge-30 s | 31.122 | 1.052 | 58.669 | 8.139 | | | | |
| Signal Merge-60 s | 24.041 | 0.633 | 60.228 | 6.228 | | | | |
| Signal Merge-90s | 26.052 | 0.411 | 60.203 | 8.062 | | | | |
| Signal Merge-120s | 29.69 | 0.442 | 58.979 | 11.621 | | | | |

**Table 3.26 Weighted Process to Determine Ideal Merge Concept for 3-to-1 Lane Configuration and 1800 pcphpl.**

| Weighted Decision-making for 3-to-1 Lane Configuration with 1800 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 64.967 | LM | 63.219 | | | | |
| SM30s | 46.491 | SM60s | 56.493 | SM90s | 56.173 | SM120s | 50.438 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM60s | 20.431 | | | | | | |

**Table 3.27 VISSIM Outputs for 3-to-1 Configuration and 2000 pcphpl.**

| 3 to 1 Configuration: 2000 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **3.022** | **0.008** | **65.223** | 0.224 | **66.411** | 0 | 0 | 0 |
| Late Merge | 3.364 | 0.01 | 65.14 | **0.206** | 66.253 | 0 | 0 | 0 |
| Signal Merge-30 s | 63.04 | 1.912 | 52.674 | 12.852 | | | | |
| Signal Merge-60 s | 24.234 | 0.484 | 60.133 | 7.038 | | | | |
| Signal Merge-90s | 28.16 | 0.47 | 59.3 | 9.13 | | | | |
| Signal Merge-120s | 58.515 | 0.76 | 53.948 | 19.192 | | | | |

**Table 3.28 Weighted Process to Determine Ideal Merge Concept for 3-to-1 Lane Configuration and 2000 pcphpl.**

| Weighted Decision-making for 3-to-1 Lane Configuration with 2000 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 64.196 | LM | 60.929 | | | | |
| SM30s | 33.142 | SM60s | 59.711 | SM90s | 54.643 | SM120s | 36.077 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM60s | 21.253 | | | | | | |

**Table 3.29 VISSIM Outputs for 3-to-1 Configuration and 2200 pcphpl.**

| 3 to 1 Configuration: 2200 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **7.47** | **0.033** | **64.08** | **1.983** | **66.336** | **0** | **0** | **0** |
| Late Merge | 65.804 | 0.823 | 53.244 | 15.219 | 33.321 | 183.67 | 705.67 | 1111 |
| Signal Merge-30 s | 213.57 | 3.495 | 35.02 | 19.304 | | | | |
| Signal Merge-60 s | 74.872 | 1.34 | 52.369 | 19.692 | | | | |
| Signal Merge-90s | 198.1 | 3.166 | 36.327 | 56.039 | | | | |
| Signal Merge-120s | 199.3 | 3.116 | 36.661 | 61.486 | | | | |

**Table 3.30 Weighted Process to Determine Ideal Merge Concept for 3-to-1 Lane Configuration and 2200 pcphpl.**

| Weighted Decision-making for 3-to-1 Lane Configuration with 2200 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 85 | LM | 23.104 | | | | |
| SM30s | 34.22 | SM60s | 59.803 | SM90s | 29.11 | SM120s | 28.954 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **60** | | | | | | |
| SM60s | 19.594 | | | | | | |

The 3-to-1 lane configuration with 2400 pcphpl demand, shown in Table 3.31, yields outputs that could support early or late merge. Although the average speed is greater for early merge, the average stopped delay per vehicle, average queue length, and maximum queue length support late merge as the better merge concept. However, using the weighted system, early merge produced 78.5 points, compared to 65.9 points for late merge. Thus, as a result of the point allocation being less for the four measures that are only applicable for early merge and late merge, early merge is the more efficient merge concept. Like the 3-to-2 lane configuration, the selection of early merge over late merge is concerning because with demand increasing to 2400 pcphpl, lanes become more congested. As a result, this congestion should increase the likelihood for queue jumping, driving in lane(s) that are closed, as well as other dangerous actions. However, since these types of behavior cannot be modeled in VISSIM, these outputs may have error that cannot be quantified. Signal merge with 60 second cycle lengths is the optimal signal merge concept because it is best in three of the four measures. The outputs suggest that early merge should be the ideal merge concept as shown in Table 3.32, but as a result of potentially significant error, signal merge with 60 second cycle lengths is used for the purpose of general trends in Tables 3.35 and 3.36.

**Table 3.31 VISSIM Outputs for 3-to-1 Configuration and 2400 pcphpl.**

| 3 to 1 Configuration: 2400 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | **189.59** | **2.6487** | **38.047** | 62.108 | **20.539** | 1136 | 2305 | **4057.3** |
| Late Merge | 293.29 | 3.91 | 29.505 | 42.594 | 5.693 | **1036** | **1158** | 4689.3 |
| Signal Merge-30 s | 413.307 | 5.343 | 23.714 | **24.031** | | | | |
| Signal Merge-60 s | 262.841 | 4.315 | 31.371 | 49.911 | | | | |
| Signal Merge-90s | 364.355 | 6.705 | 25.86 | 75.431 | | | | |
| Signal Merge-120s | 396.878 | 7.418 | 24.501 | 88.987 | | | | |

**Table 3.32 Weighted Process to Determine Ideal Merge Concept for 3-to-1 Lane Configuration and 2400 pcphpl.**

| Weighted Decision-making for 3-to-1 Lane Configuration with 2400 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 78.49 | LM | 65.924 | | | | |
| SM30s | 45.913 | SM60s | 54.815 | SM90s | 40.536 | SM120s | 37.383 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| **EM** | **58.036** | | | | | | |
| SM60s | 47.055 | | | | | | |

With a user demand of 2600 pcphpl, Table 3.33 shows the VISSIM outputs. Using the weighted system in Table 3.34, late merge is more efficient for traffic operations than early merge because late merge minimizes delay and stopped delay, while maximizing average speed. In addition to minimizing delay, signal merge with a 60 second cycle length in the 2600 pcphpl case allows for a higher average speed of 23.2 mph, compared to the 22.5 mph average speed of late merge. For these reasons, signal merge with a 60 second cycle length is the optimal merge concept for a 3-to-1 lane configuration and 2600 pcphpl.

**Table 3.33 VISSIM Outputs for 3-to-1 Configuration and 2600 pcphpl.**

| 3 to 1 Configuration: 2600 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Avg Delay Time per Vehicle (s) | Avg # of Stops per Vehicle | Avg Speed (mph) | Avg Stopped Delay per Vehicle (s) | Avg Speed on Link Prior to Closure (mph) | Avg Queue Length (ft) | Max Queue Length (ft) | # of Stops within Queue |
| Early Merge | 498.891 | 8.448 | 20.38 | 151.356 | **6.121** | 1136 | 2305 | **4057.33** |
| Late Merge | 436.494 | **6.481** | 22.504 | 58.755 | 4.994 | **1092** | **1163** | 4849 |
| Signal Merge-30 s | 551.589 | 7.32 | 18.826 | **30.689** | | | | |
| Signal Merge-60 s | **424.405** | 7.446 | **23.229** | 57.206 | | | | |
| Signal Merge-90s | 522.815 | 9.609 | 19.781 | 84.382 | | | | |
| Signal Merge-120s | 563.83 | 10.052 | 18.644 | 97.938 | | | | |

**Table 3.34 Weighted Process to Determine Ideal Merge Concept for 3-to-1 Lane Configuration and 2600 pcphpl.**

| Weighted Decision-making for 3-to-1 Lane Configuration with 2600 pcphpl | | | | | | | |
|---|---|---|---|---|---|---|---|
| EM | 69.3 | LM | 83.263 | | | | |
| SM30s | 51.597 | SM60s | 55.195 | SM90s | 44.521 | SM120s | 41.522 |
| Reweighted using 4 common measured characteristics | | | | | | | |
| LM | 58.558 | | | | | | |
| **SM60s** | **58.704** | | | | | | |

### 3.3.2.10 VISSIM Merge Concept Conclusions

In general, the merge concepts that provide for ideal management of traffic are supported by the various VISSIM outputs. In addition, assumptions about merge concept trends were accurate in that, lower demand is best managed by early merge, low to moderate demand by late merge, and high demand by signal merge. Early merge is beneficial in lower demand situations and allows for freeway users to merge into gaps prior to the distraction of the work zone. Late merge allows users to utilize the entire roadway capacity until the actual work zone, while fixed signal merge is best for high demand situations and can significantly reduce lane-change conflicts at work zone closures. Signal merge should also reduce rear-end conflicts for work zones with more than one lane closed. For both safety and minimizing lost time or delay in freeway work zone situations, short cycle lengths less than approximately 60 seconds should not be used. In addition, cycle lengths with 120 seconds or more should not be used because roadway users would get frustrated and impatient with long cycle lengths, potentially leading to queue jumping and driving in the closed lane(s). The VISSIM conclusions below suggest that FCSMC significantly increases flow throughput at work zones and overall improves traffic operations with saturated or heavily congested conditions. If current organizational practices do not support the use of signal merge, late merge can be inserted in the summary recommendation tables where signal merge is shown.

Thus, Table 3.35 shows the overall optimal merge concept by lane configuration and VISSIM input demands, while Table 3.36 shows the overall optimal merge concept using volume and capacity. Table 3.37 shows the optimal signal merge cycle lengths by lane configuration and VISSIM input demands, while Table 3.38 shows the optimal cycle lengths using volume and capacity. The outputs in Tables 3.35 and 3.37 use input values based on the Highway Capacity Manual. As previouosly mentioned, the Highway Capacity Manual typically suggests that freeway lane capacities range from 1800 to around 2300 pcphpl ("Guide for Highway," 2013). Assuming ideal conditions and a capacity around 2300 pcphpl, input demand values were selected around that capacity. Thus, Table 3.35 suggests that with slightly less than idea conditions, the capacity should be around 2200 pcphpl. Looking from Table 3.35 to 3.36 and 3.37 to 3.38, the 2200 pcphpl changes to essentially volume equal to capacity. Additionally, for 1800 and 2000 pcphpl, the volume is said to be less than capacity, while for 2400 and 2600 pcphpl, the volume is more than capacity. However, if capacity is unknown or different from the assumptions that were made, Tables 3.36 and 3.38 can be used as generic tables that show the optimal merge concept and ideal signal merge concept, based on the volume-to-capacity ratio. If the capacity is in fact different from the assumption, other input demand values should be selected around that capacity value and updated in VISSIM, to still use the ideal merge concepts found from this analysis as a comparison. Regardless, as the demand is less than capacity, early merge is the ideal merge concept. When demand approaches capacity, there is a shift from early to late to signal merge. As demand exceeds capacity, signal merge with 60 or 90 second cycle lengths can be used as the ideal merge concept.

**Table 3.35 Overall Optimal Merge Concept using VISSIM Inputs.**

| | User Demand | | | | |
|---|---|---|---|---|---|
| | 1800 pcphpl | 2000 pcphpl | 2200 pcphpl | 2400 pcphpl | 2600 pcphpl |
| 2-to-1 | EM | EM | SM60s | SM90s | SM90s |
| 3-to-2 | EM | EM | EM | SM60s | SM60s |
| 3-to-1 | EM | EM | EM | SM60s | SM60s |

**Table 3.36 Overall Optimal Merge Concept.**

| | User Demand | | | | |
|---|---|---|---|---|---|
| | V < C | V < C | V = C | V > C | V > C |
| 2-to-1 | EM | EM | SM60s | SM90s | SM90s |
| 3-to-2 | EM | EM | EM | SM60s | SM60s |
| 3-to-1 | EM | EM | EM | SM60s | SM60s |

**Table 3.37 Optimal Cycle Lengths for Signal Merge using VISSIM Inputs.**

| | User Demand | | | | |
|---|---|---|---|---|---|
| | 1800 pcphpl | 2000 pcphpl | 2200 pcphpl | 2400 pcphpl | 2600 pcphpl |
| 2-to-1 | 60 sec | 60 sec | 60 sec | 90 sec | 90 sec |
| 3-to-2 | 60 sec | 60 sec | 60 sec | 60 sec | 60 sec |
| 3-to-1 | 60 sec | 60 sec | 60 sec | 60 sec | 60 sec |

**Table 3.38 Optimal Cycle Lengths for Signal Merge.**

| | User Demand | | | | |
|---|---|---|---|---|---|
| | V < C | V < C | V = C | V > C | V > C |
| 2-to-1 | 60 sec | 60 sec | 60 sec | 90 sec | 90 sec |
| 3-to-2 | 60 sec | 60 sec | 60 sec | 60 sec | 60 sec |
| 3-to-1 | 60 sec | 60 sec | 60 sec | 60 sec | 60 sec |

### 3.3.3 VISSIM Input Demands based on Real Site Data

If VISSIM input demands are not assumed and real traffic data will instead be used, the first step is to assess traffic conditions before the work zone is in place. The initial step required to assess the before work zone conditions is to collect traffic demand data. Ideally, data should be collected 24 hours per day, 7 days a week, during a representative week of the year. Oftentimes, it is difficult to obtain a complete set of data and it may be necessary to utilize information obtained for a single day, or even extrapolate peak-hour data. Further, in some cases, data collection may not be feasible; under such circumstances, the transportation agency in charge of the work zone and merging process can contact the corresponding Metropolitan Planning Organization and request an estimation of traffic volumes at the desired location based on the corresponding regional model. The collected or synthetized data is used to generate a plot, such as the one displayed in Figure 3.8, that displays volume in vehicles per hour against hours of the day. This plot is useful to understand the nature of the travel demand through the work zone area. For example, Figure 3.8 shows a case where similar volume counts occur on Monday through Thursday with slight variations on Friday. The Saturday and Sunday data are significantly different from week days and show greater volume in the early morning hours than during the week.

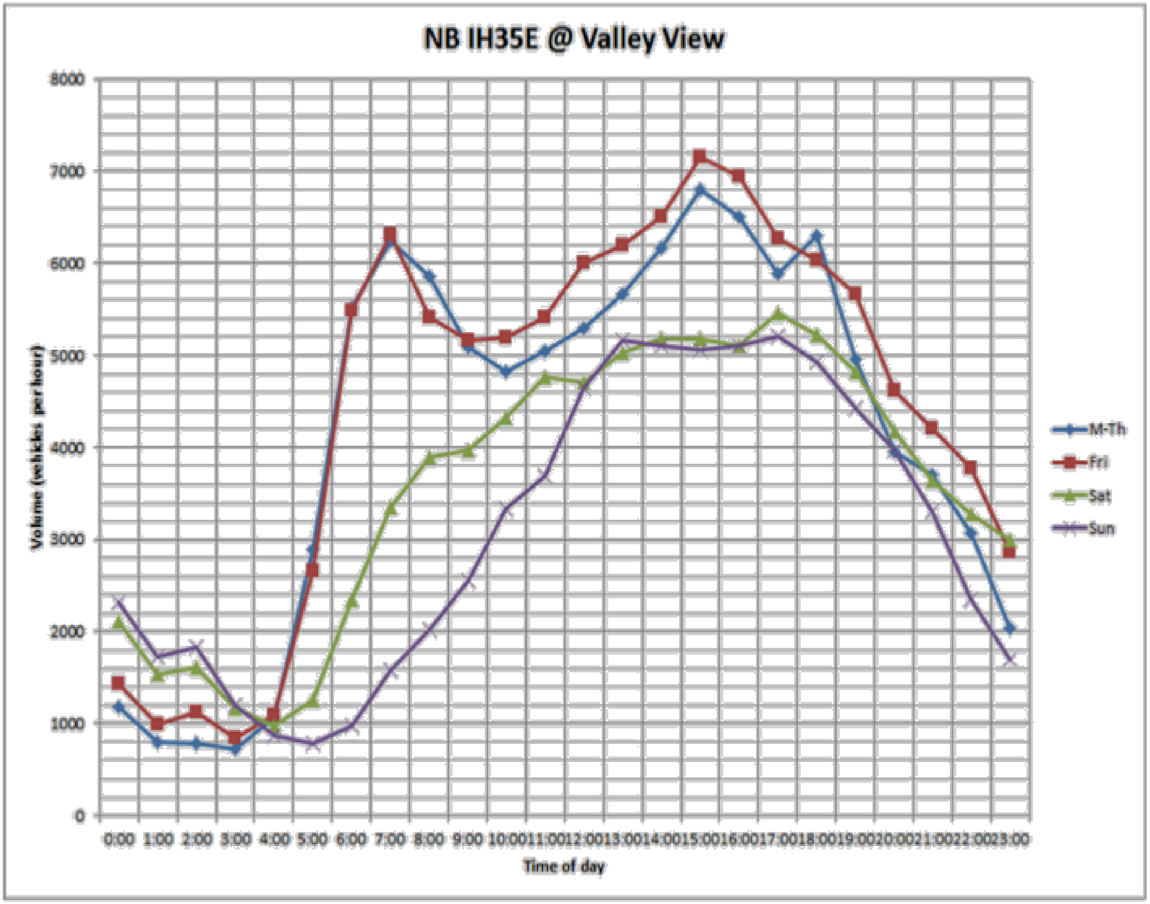



**Figure 3.8 Example Count Data from I-35E near Dallas, Texas.**

The second step in the process of assessing before conditions involves analyzing hourly volume-to-capacity conditions. A table like Table 3.39 may be used to determine which hours of the day would be best for freeway work zone activity. In Table 3.39, period A represents weekday peak conditions and the full capacity of the corridor is needed. Therefore, between the hours of 6 am and 8 pm on Monday through Friday, work zone lane closure(s) cannot take place because the full roadway capacity is needed. Periods B, C, and D are weekend peak, off-peak, and night respectively, and require less than full capacity. Thus, these times would be the only options for a freeway work zone lane closure(s), but the transportation agency in charge would have to determine which of these hours would be best for roadway operations and for the contractor.

**Table 3.39 Hourly Volume-to-Capacity Conditions for I-35E Example Site near Dallas, Texas.**

| | Northbound IH 35E | | | |
|---|---|---|---|---|
| | Sunday | Monday-Thursday | Friday | Saturday |
| 0:00 | D | D | D | D |
| 1:00 | D | D | D | D |
| 2:00 | D | D | D | D |
| 3:00 | D | D | D | D |
| 4:00 | D | D | D | D |
| 5:00 | D | D | D | D |
| 6:00 | D | A | A | D |
| 7:00 | D | A | A | C |
| 8:00 | D | A | A | C |
| 9:00 | D | A | A | B |
| 10:00 | D | A | A | B |
| 11:00 | B | A | A | B |
| 12:00 | B | A | A | B |
| 13:00 | B | A | A | B |
| 14:00 | B | A | A | B |
| 15:00 | B | A | A | B |
| 16:00 | B | A | A | B |
| 17:00 | B | A | A | B |
| 18:00 | B | A | A | B |
| 19:00 | B | A | A | B |
| 20:00 | B | A | A | C |
| 21:00 | D | C | C | C |
| 22:00 | D | D | D | D |
| 23:00 | D | D | D | D |

| | |
|---|---|
| A | Weeday peak |
| B | Weekend peak |
| C | Off-peak |
| D | Night |

# Chapter 4. Analysis

## 4.1 Introduction to Safety Analysis

In order to properly determine the ideal merge concept for varying lane configurations and demands, it is important to consider both delay and safety. While working on the TxDOT Project # 0-6704: Reduction of Motorists' Delay and Crash Potential Upstream of Highway Work Zones, my main focus was on delay and operational efficiency. While I presented on both delay and safety, the majority of the safety analysis was completed by my colleagues at Texas Southern University. For completeness, the safety analysis is summarized in this chapter.

This chapter provides analysis of traffic safety performance in freeway work zone areas, with and without Fixed-Cycle Signal Merge Control (FCSMC), under various traffic and geometric conditions. To assess the signal merge safety performance, a two-stage, simulation-based approach was used. In the first stage, microsimulation models were developed and calibrated based on field data to generate vehicle trajectories. In the second stage, Siemens Surrogate Safety Assessment Model (SSAM), developed by the FHWA, was employed to identify potential conflicts under different conditions. In this task, a set of hypothesized work zone scenarios were tested. The results of this study showed that in most cases, the FCSMC or Fixed Cycle Work Zone Traffic Signal Control (FCWZTSC) strategy can significantly reduce conflicts caused by work zone situations, especially lane-change conflicts. However, FCWZTSC is not suggested when the traffic volume is relatively light and it is also not recommended to use short signal cycle lengths, like 30 seconds or less.

The MUTCD provides basic guidelines for traffic control devices in work zone areas, including placing "Road Work Ahead" signs, flash yellow arrows, etc. It also suggests the location where these signs should be placed. However, MUTCD traffic control strategies cannot effectively control work zone congestion and result in extremely long queues and problematic driving behaviors, such as queue jumping. As a result, innovative traffic control strategies were developed to reduce congestion and crash potential in work zones. The Fixed Cycle Work Zone Traffic Signal Control is an example innovative strategy. In the following sections, the FCWZTSC strategy is compared to traditional traffic control strategies like early and late merge to evaluate the safety impacts of FCWZTSC.

### 4.1.1 Introduction to Concepts in SSAM

To supplement the existing studies, simulation studies were performed by the researchers using VISSIM, in conjunction with Surrogate Safety Assessment Model, or SSAM.

A traffic conflict modification factor (TCMF) was developed in this study. Similar to CMF presented in the American Association of State Highway and Transportation Officials Highway Safety Manual (AASHTO HSM), TCMF factors were provided for estimating the expected changes of traffic conflict frequency after implementing specific geometric changes associated with an auxiliary lane. The TCMF was calculated as follows:

$$\text{TCMF} = \frac{\text{Traffic Conflict Frequency after Treatment}}{\text{Traffic Conflict Frequency before Treatment}} \times 100\% \qquad \textbf{(}\text{Equation 4.1)}$$

A TCMF with a value less than 1.0 means the treatment can potentially reduce the occurrence of traffic conflicts and improve the safety performance. Conversely, a TCMF with a value greater than 1.0 suggests that the treatment can potentially increase the occurrence of traffic conflicts and compromise safety performance.

The traditional way of assessing safety impacts is to analyze historical crash data at the study sites. Recognizing the fact that crashes are rare events and subject to randomness inherent to small numbers, the crashes are normally observed over a relatively long period, such as 1-6 years. This process to reveal the need for remediation is relatively slow and not applicable to conduct safety assessment for design of roadways that have not been built or operational strategies that have not been applied in the field.

An available alternative to assess safety impacts of roadway designs is to use microscopic traffic simulation models to obtain useful safety surrogate measures that can reflect their safety impacts. A typical procedure for applying such methods is as follows. First, microscopic traffic simulation scenarios are developed characterizing the roadway designs to be examined. Then, together with operational measures, safety surrogate measures, which can be derived from the results of the microscopic traffic simulation, are computed, extracted, and analyzed to estimate the conflict frequency and the safety risk. In this task, the SSAM developed by Siemens was used for assessing the safety impacts of various design options. By directly processing vehicle trajectory data obtained from the results of microscopic traffic simulation, it enables researchers to estimate traffic conflict frequency. The method for estimating traffic conflict frequency can be seen in Figure 4.1.

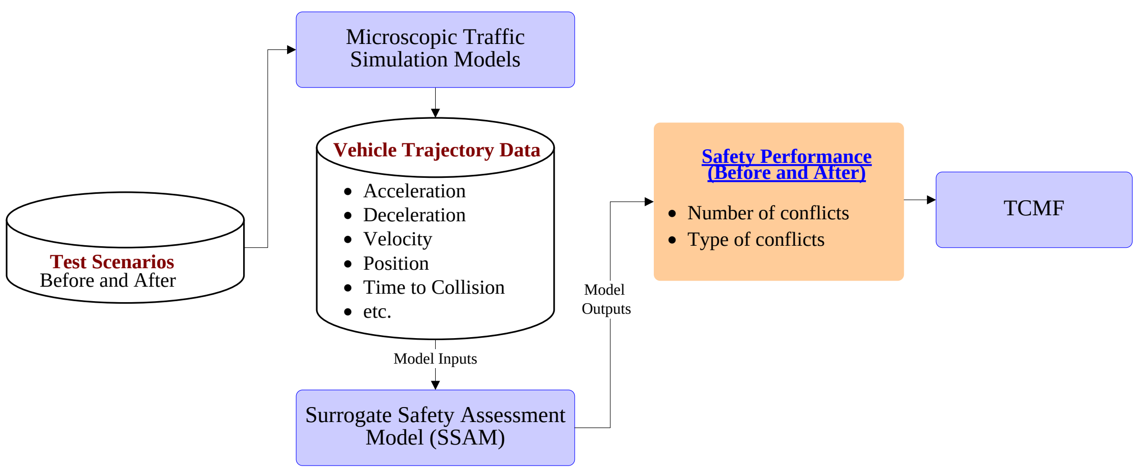



**Figure 4.1 Method of Estimating Traffic Conflict Frequency.**

## 4.2 Scenario Design and Experimental Results—Stage One: VISSIM Model

Various scenarios were designed to calculate TCMF under different conditions, including traffic volume, number of lanes, number of closed lane(s), and cycle lengths. Below is an explanation of a set of hypothesized work zone scenarios.

### 4.2.1 Hypothesized Work Zone Scenarios

According to the VISSIM simulation experiments conducted, four different levels of traffic demand were tested, including 1800, 2000, 2200, and 2400 vphpl. In addition to the four traffic demands, four different cycle lengths were selected, including 30, 60, 90, and 120 seconds. In addition, three different types of roadway closure were designed, which are:

- Two-lane freeway, one lane closed,
- Three-lane freeway, one lane closed,
- Three-lane freeway, two lanes closed.

Therefore, 48 scenarios were created for FCWZTSC and 12 baseline scenarios without FCWZTSC, including volume levels and roadway closure types. Please refer to Figure 4.2 for the layout of hypothesized work zone scenarios.

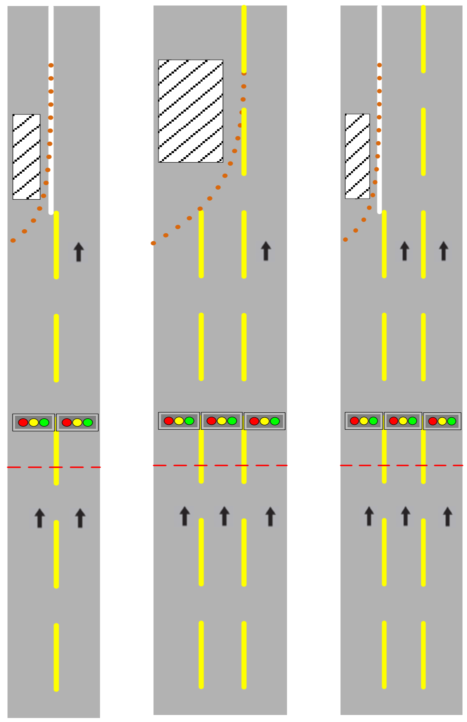


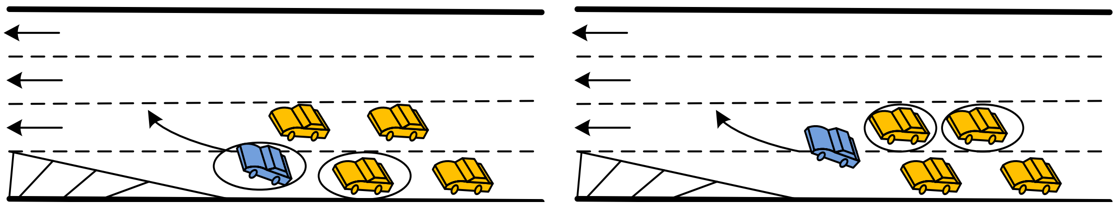
**Figure 4.2 Layouts of Hypothesized Work Zone Scenarios.**

### 4.3 Stage Two: SSAM Model Traffic Conflicts

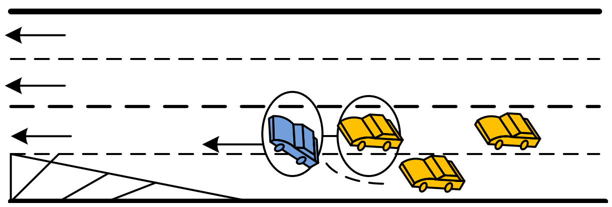
In all experiments, the simulation of each sub-scenario covered 90 simulation minutes, and was conducted with 10 or 20 different random seeds. Each run generated one vehicle trajectory file, which was then processed by SSAM producing estimates of traffic conflicts for each scenario.

#### 4.3.1 Conflicts Related to Work Zone Closure

There are two types of conflicts highly related to work zone closures, which include rear-end and lane-change conflicts. Figure 4.3(a) illustrates two instances of rear-end conflicts, and 4.3(b) shows a typical lane-change conflict.



(a)



(b)

**Figure 4.3  Conflicts Related to Work Zone Closure.**

## 4.4 SSAM Outputs

### 4.4.1 Outputs for 2-to-1 Lane Configuration

The first modeled geometric design was the 2-to-1 lane configuration with four different volume levels, including 1800, 2000, 2200, and 2400 vphpl. As previously mentioned, for the signalized lane control strategy, four different cycle lengths were tested, including 30, 60, 90 and 120 seconds. Figures 4.4 and 4.5 are the lane-change and rear-end conflicts comparison results.

From Figure 4.4, it can be seen that in all conditions except 1800 vphpl, implementing the FCWZTSC strategy could significantly reduce lane-change conflicts. Since there is minimal traffic congestion at the work zone merge point, vehicles can easily pass the merge point without conflict. Thus, the traditional traffic control strategy works adequately. Under light traffic demands, use of the FCWZTSC strategy will increase vehicle stops and cause more traffic conflicts. In addition, the 30 second cycle length causes the most conflicts and is not recommended. Figure 4.5 shows that implementation of the signalized merge control strategy (FCWZSC) increases rear-end conflicts for all volume conditions, especially for shorter cycle lengths. This is reasonable because use of FCWZSC will cause more vehicle stops when the cycle length is short, which increases the chance of rear-end conflicts.

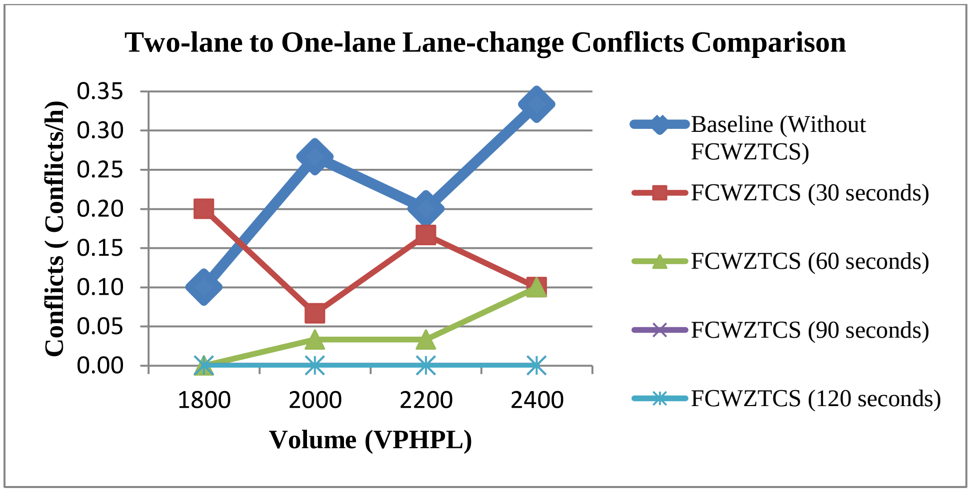



**Figure 4.4 Lane-change Conflicts Versus Cycle Length for 2-to-1 Lane Configuration.**

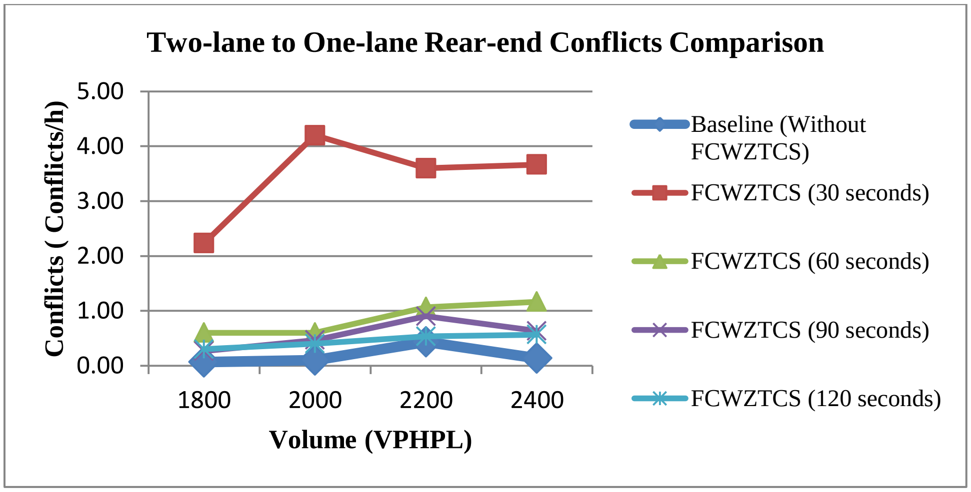



**Figure 4.5 Rear-end Conflicts Versus Cycle Length for 2-to-1 Lane Configuration.**

### 4.4.2 Outputs for 3-to-2 Lane Configuration

Figures 4.6 and 4.7 show the lane-change and rear-end conflict comparison results for the 3-to-2 lane configuration. For light traffic demands like 1800 or 2000 vphpl, the MUTCD lane control strategy works well because it has the least lane-change and rear-end conflicts. With an increase in volume, more traffic conflicts occur due to the congested traffic condition, thus highlighting the benefits of FCWZSC.

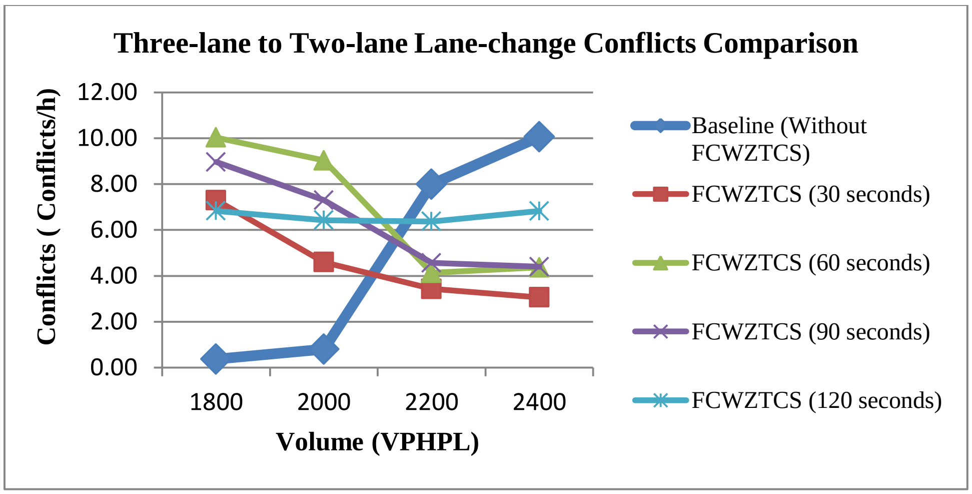



**Figure 4.6 Lane-change Conflicts Versus Cycle Length for 3-to-2 Lane Configuration.**

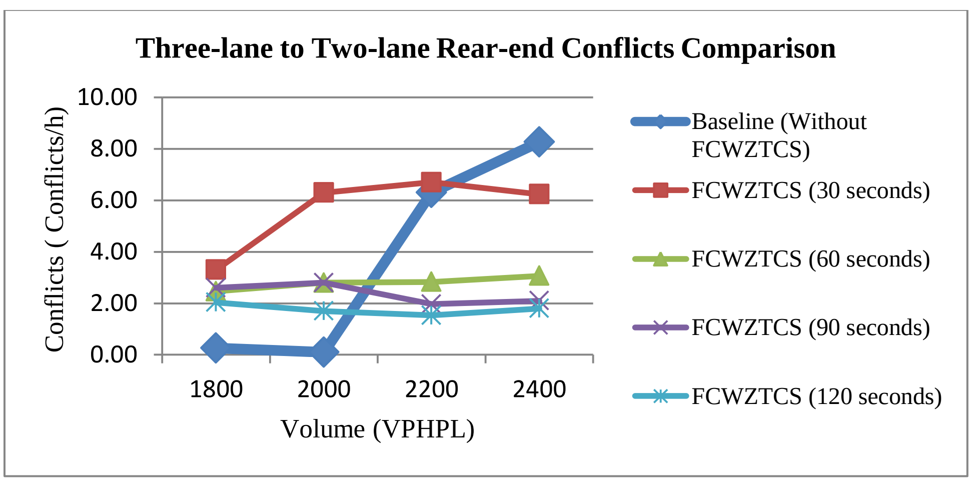



**Figure 4.7 Rear-end Conflicts Versus Cycle Length for 3-to-2 Lane Configuration.**

### 4.4.3 Outputs for 3-to-1 Lane Configuration

Figures 4.8 and 4.9 show the lane-change and rear-end conflicts comparison results for the 3-to-1 lane configuration. From Figure 4.8, it can be seen FCWZTSC can significantly reduce lane-change conflicts, especially when the traffic demand is high.

Similar to the other two lane configurations, Figure 4.9 shows that when traffic demand is lighter as represented here by cases of 1800, 2000, or 2200 vphpl, the FCWZTSC does not reduce rear-end conflicts. When traffic demand reaches 2400 vphpl, FCWZTSC starts to work well and reduces rear-end conflicts.

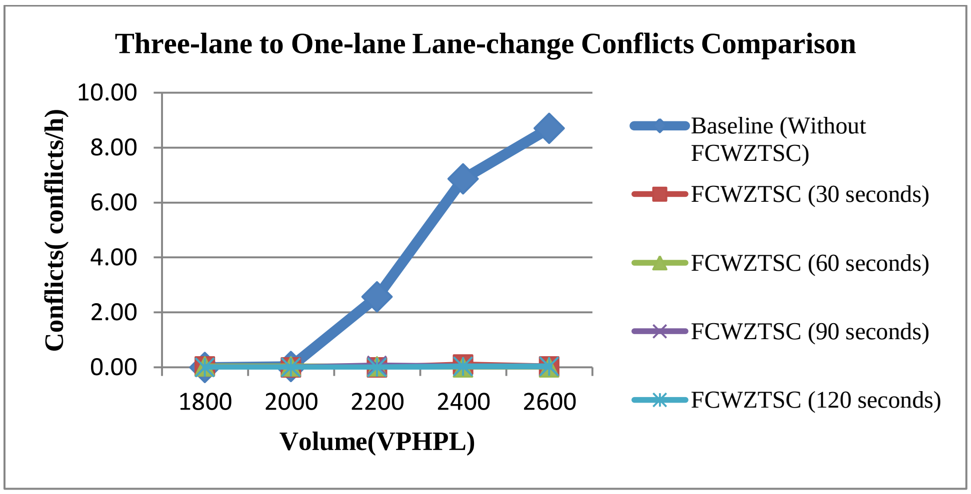



**Figure 4.8 Lane-change Conflicts Versus Cycle Length for 3-to-1 Lane Configuration.**

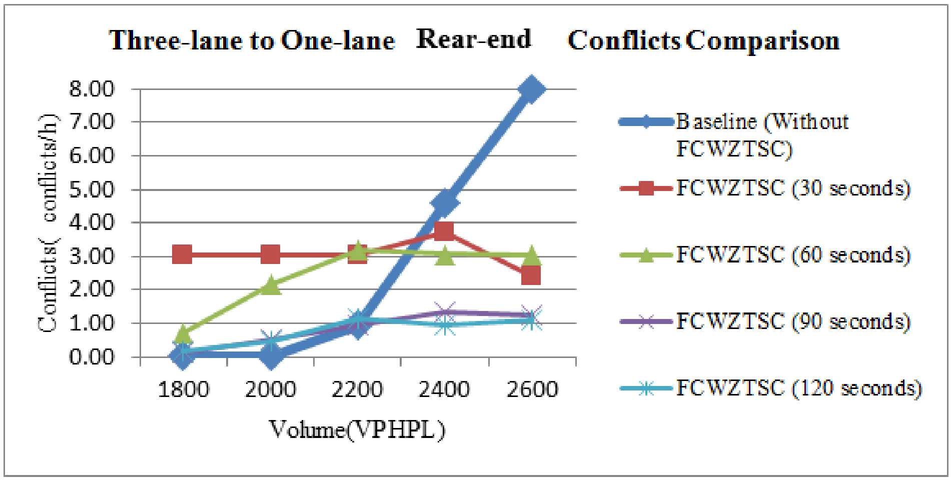



**Figure 4.9 Rear-end Conflicts Versus Cycle Length for 3-to-1 Lane Configuration.**

# Chapter 5. Recommendations and Conclusions

## 5.1 General Conclusions

As previously introduced, three families of merge concepts, early merge, late merge, and signal merge, respectively, offer advantages and disadvantages in terms of operational efficiency and safety. The work documented here generally shows early merge as preferred with lighter traffic demands, such that conditions where the volume-to-capacity ratio is less than one. If demand approaches capacity and queuing occurs, late merge is preferred. Both early and late merge can be implemented as static or dynamic, such that dynamic early merge can switch to early merge based on traffic conditions. Thus, a merge concept that is set up “static” uses signage that displays a single message in the same location at all times, regardless of traffic conditions. Conversely, “dynamic” refers to real-time control measures that are used to determine which signage should be used upstream to inform drivers of upcoming conditions.

In order to determine the appropriate merge concept based on varying demands and lane configurations, various conclusions were made after using VISSIM in Chapter 3.3.2. The early merge concept works best with low volume conditions and becomes highly problematic when traffic demand approaches or exceeds work zone capacity. Under these conditions with higher demand, incidents of queue jumping, excessive lane changing and crashes tend to escalate. In cases where hours and days of work zone activity must include times when the demand approaches or exceeds capacity, late merge and signal merge are the best options. Late merge schemes generally are designed to use all available lane space prior to the work zone for queue storage, therefore, they provide the best available procedure if traffic demand approaches or exceeds work zone capacity. In addition, for times in which demand exceeds capacity of the work zone, use of the signal controlled merge offers promise to reduce queue jumping, lane changing and associated crashes.

Traffic modeling through simulation is a vital tool for transportation research. Simulators allow for a window into the real world that can be calibrated to match field conditions. Studies mentioned above used simulators to analyze variable lane configurations, divergence, and differing control methods. Using these programs the analyst can maintain consistent parameters and gain accurate comparisons across different scenarios. Primarily, VISSIM was the simulator of choice for the above evaluations and is a behavior-based traffic simulator that can optimize complex technical systems while being calibrated to real world situations.

**5.2 VISSIM Simulation and DTA Modeling Conclusions**

From VISSIM simulations and DTA models, the following conclusions were made. If the hours and days of work zone activity can be chosen so that traffic demand does not exceed work zone capacity, an early merge scheme will provide maximum safety and minimum user delay. Under low volume conditions, early merge can enable little or no delay for travelers through the work zone. Early merge concepts though become highly problematic when traffic demand approaches or exceeds work zone capacity. Under these conditions, incidents of queue jumping, excessive lane changing and crashes tend to escalate.

However, if hours and days of work zone activity must include times in which traffic demand approaches or exceeds capacity, the late merge concept is likely the best option. Late merge schemes generally are designed to use all available lane space prior to the work zone for queue storage, therefore, they provide the best available procedure if traffic demand approaches or exceeds work zone capacity.

For times in which demand exceeds capacity of the work zone, use of the signal controlled merge offers promise to reduce queue jumping, lane changing and associated crashes.

In order to determine the ideal merge concept for a specific work zone site, estimation of the work zone traffic demand should be desirably based on counts or at least estimates of traffic volumes prior to work zone installation. Although every work zone is unique, generally the traffic demand during work zone activity will be less than demand before work zone activation, that is, diversion of traffic from the work zone is almost always non-zero. In order to estimate the amount of traffic that will divert from the counted demand, estimation of work zone traffic diversion should be taken into account. Dynamic Traffic Assignment (DTA) is the best available tool to estimate the amount of traffic diversion that can be expected. This DTA model can yield link traffic volumes, as opposed to link demands produced by a static assignment process. If DTA is not yet available for the work zone location, a Static Traffic Assignment (STA) model offers a reasonable second choice. STA has serious limitations as far as realistically representing the process that leads to congestion and increased travel time, but in a comparison of the before and after conditions in the work zone area, it does provide value. STA models are currently available in all urban and suburban Metropolitan Planning Organization shops.

### 5.3 Fixed Cycle Work Zone Traffic Signal Control Safety Conclusions

In this study, the safety impacts of the use of Fixed Cycle Work Zone Traffic Signal Control, otherwise known as signal merge, at freeway work zones under various traffic and geometric conditions was examined. Instead of actual crash rates, traffic conflicts derived from the microscopic traffic simulation results were used as safety surrogates. Traffic simulation models were developed and calibrated based on the field data. Based on the results of the traffic conflict analysis, the following conclusions can be drawn. First, FCWZTSC can significantly reduce the lane-change conflicts at work zone closures, generally as demand exceeds 2,200 vphpl. The addition of signals at any location may increase rear-end conflicts and this is true at work zones, in particular with only one lane closed. However, for work zones with more than one lane closed, as in the case of a 3-to-1 lane configuration, use of FCWZTSC will result in a significant reduction of both lane-change and rear-end conflicts.

In general, FCWZTSC is not recommended for low traffic volumes, like 1800 vphpl and it is also not recommended to use short signal cycle lengths, generally the minimum recommend cycle length is approximately 60 seconds. Thus, these safety conclusions support the results from VISSIM, which suggest that FCWZTSC or signal merge is applied most safely in scenarios where demand exceeds capacity. The safety results suggest that the addition of FCWZTSC can significantly improve lane-change conflicts as demand begins to exceed capacity.

### 5.4 Recommendations for Future Research

Although the general conclusions and recommendations for different applications of early merge, late merge, and signal merge were supported by the VISSIM analysis, there were several shortcomings. In order to run simulations for different roadway configurations, user demand, and merge concepts, various assumptions were made that should be researched further. The purpose of this evaluation of different merge concepts for freeway work zones was to provide a framework that begins to assess benefits and shortcomings of the various merge concepts in different applications. Through the literature review research, it was concluded that there has been sufficient research studying different merge concepts. However, the motivation for my research was to study the different applications of various merge concepts using the same analysis tool. The output necessary to conduct this study could have been obtained from both VISSIM and CORSIM, but the 3-dimensional graphic and animation capabilities of VISSIM were essential for someone unfamiliar with microscopic simulation. The ability to have 3-dimensional animation capabilities allowed the freeway to be modeled appropriately and find areas of conflict within the model. While modeling early merge with a 3-to-2 lane configuration, for example, closure on one lane on a link prior to the work zone lane closure was first attempted. However, the 3-dimensional animation capabilities allowed for visualization of the system to determine that one lane in multiple links prior to the work zone needed to be closed because it took a few seconds for the vehicles in the animation to find a gap to merge. When only one link prior to the work zone was closed, vehicles could not find a gap to merge and would continue driving on the closed lane. Therefore, using the outputs and the 3-dimensional animation, it was easier to determine how many links prior to the lane closure were needed. By closing one lane on three links prior to the work zone, or approximately one-quarter mile, the animation showed that drivers were able to find a gap to merge almost instantly and avoid queuing in the closed lane. In hindsight, more than three links prior to the work zone should have been closed, to determine the number of links closed that would produce the most efficient traffic operations.

In order to determine the ideal merge concept for each combination of lane configuration and user demand, several simplifications were made that should be explored by future researchers. Specifically, the user demand, in passenger cars per hour per lane included no trucks. The first consideration should be to determine the likelihood that the no truck assumption would significantly change the results. In order to determine this likelihood, the fraction of trucks that would have been on the freeway should be considered. For instance, if the percentage of trucks is less than 10 percent, then the assumption of no trucks likely did not significantly affect the output. However, if the percentage of trucks is greater than 10 percent, the no truck assumption could significantly affect the output. Thus, this assumption is a function of the roadway that is being modeled. If the ideal merge concepts are to be determined for a specific roadway with a known percentage of trucks, then the general 10 percent rule can be applied to determine if an assumption of no trucks would be allowable. However, if a specific freeway was being modeled and the percentage trucks could likely be determined, that information should be included in the VISSIM simulations. In addition to heavy vehicle inputs, the simulations assumed equal demand in each lane leading to equal green times for each lane with signal merge. The assumption that all lanes have equal demand should be assessed in further research because if vehicles are able to perceive the work zone in advance of the signal merge and exit the freeway before the signal merge, this user choice could change the equal demand scenario.

Another assumption that is a function of the roadway that is being modeled is the presence of horizontal curvature of the roadway. For example, my VISSIM model was meant to be used for general cases, as a baseline. However, if the modeler knows the horizontal curvature of the roadway, it should also be included as a variable in VISSIM. Additionally, if the roadway includes vertical curvature or significant grades, this should also be inputted into VISSIM.

The baseline VISSIM model that was developed only had one opportunity for inflow and one opportunity for outflow. Thus, the freeway was modeled after a straight path with no entrance or exit ramps within a several miles of the work zone. The addition of entrance and exit ramps in the work zone would yield a highly variable user demand. The inclusion of entrance and exit ramps is again a function of the site that is being modeled. If there is an exit ramp just before the work zone, for example, the ideal merge concept may be different than the model that was developed because a significant fraction may avoid going through the lane closure to avoid queuing and congestion. The addition of entrance or on-ramps to the freeway section would have allowed for another method of controlling demand through signals. As a primary source for addressing constant freeway congestion, ramp metering can be used. Ramp meters are traffic signals placed at the freeway on-ramps, that control the rate at which vehicles enter the freeway, so that the downstream capacity is not exceeded (“Ramp Metering,” 2000). By ensuring that the downstream capacity is not exceeded, the freeway would be able to carry the maximum volume, or capacity, at a uniform speed (“Ramp Metering,” 2000). Thus, in addition to further exploring the previous assumptions, future researchers should determine if ramp metering would also be a consideration to achieve the most efficient traffic operations. Future researchers should explore if ramp metering could be used in combination with other merge techniques at the work zone and also the ideal cycle length for the on-ramp traffic signals.

One final area of exploration for future researchers that was briefly discussed is joint merge. As previously discussed, joint merge places signage in the advance warning area to inform users of the traffic conditions ahead. Channeling devices are used in the transition area, to move traffic out of its normal path. By using a “funnel-shaped” configuration, future researchers should explore if simultaneously merging two lanes into one would provide a significant benefit to the overall freeway efficiency. In addition, with minimal applications of joint merge in the field, future researchers should determine if joint merge would be a beneficial bridge between early and late merge. However, VISSIM forces the modeler to use connectors between links that identify the lanes that are to be connected. This feature would be problematic for using joint merge in VISSIM because just one link prior to the connector would not be attached to one lane; instead, two lanes would simultaneously connect directly to one lane.

While VISSIM or CORSIM can be used to determine the optimal merge concept based on lane configuration, demand, and other roadway characteristics, VISSIM modeled clear trends, while the outputs from CORSIM seemed less consistent. It is important to note though, that the simulation modeling is not based on any actual site. Thus, although several assumptions were made in order to generate useful outputs, the outputs yielded clear trends for changing demands and varying lane configurations that match the general hypotheses.

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